FRAMEWORK FOR ASSESSING THE POTENTIAL OF NEW TECHNOLOGIES TO CAPTURE THE AS-BUILT INFORMATION FROM PROJECT SITES

by

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Abstract

As-built information from construction project sites is often required by project participants to address various user-specific needs such as assessing the construction quality or planning for upcoming renovations, or guiding future repairs during building operations. However, most of this information is still being captured through traditional methods like tape measure, or referring to 2D drawings which are found to be inefficient. Although many data acquisition tools such as 3D laser scanning and photogrammetry currently exist, they suffer from numerous limitations such as the lack of affordability or requiring expertise to operate. This has encouraged both researchers and technology vendors to look into new alternative capture technologies that are cost effective, easy to use, and efficient. This need for better alternatives led to the rapid development of various new capture technologies that are now needed to be evaluated for construction industry purposes. With such new technologies being released regularly, there is also an increased confusion among industry professionals to identify the best suitable capture technology for addressing their specific needs.

Thus, the objective of this research is to develop a framework for evaluating the potential of new as-built information capture technologies to support construction purposes. The research also focuses on using the developed framework to evaluate the potential of two new capture technologies, mobile laser scanning and spherical imaging, that have recently been gaining traction in the construction industry. For this, a case study based research approach was developed and four construction projects were chosen as sample case studies for this work. Current industry practices for capturing the necessary as-built information to address different use case scenarios within these projects were first observed and analyzed. Then, the framework was developed by conducting an in-depth analysis of the current industry practices, reviewing relevant literature and

by also having a series of informal discussions with various project team members involved in the chosen case study projects. The potential of mobile laser scanning and spherical imaging technologies was then assessed by testing them on the relevant use case scenarios. The benefits and limitations were identified based on a structured assessment using the developed framework.

Preface

This thesis is based on the author’s work with Stantec Consulting Ltd. and other construction firms under the direct supervision of Dr. Sheryl Staub-French, Dr. Puyan Zadeh and Dr. Thomas Froese. The author is mostly responsible for identifying and setting up the research theme of this work. The author is also responsbile for the data collection, analysis and research findings presented in this work.

Part of the research findings from this work has been published as a conference proceeding: Kalyan, T. S., Zadeh, P. A., Staub-French, S., & Froese, T. M. (2016). **“Construction Quality Assessment Using 3D as-built Models Generated with Project Tango.”** *Procedia Engineering*, *145*, 1416-1423. This is presented at the International Conference on Sustainable Design, Engineering and Construction at Tempe, Arizona on May, 2016.

The thesis is intended to be submitted for a future journal publication after slight modifications.

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Acknowledgements

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I would also like to thank Dr. Puyan Zadeh for acting like my research guide and close advisor throughout this whole research work. He was always there to discuss all my queries and has offered his undivided attention and support to this research right from the start.

Finally, I would like to convey my heartfelt thanks to Dr. Thomas Froese for his key insights about the various technologies that can be useful for the construction industry. His support and guidance during my first research based course was crucial in shaping up the scope and theme for this research work.

Special mention goes to my Industry Supervisor – Aubrey Tucker who acted as my friend and mentor during this whole research. His comments and suggestions played a key role in making this research as relevant as possible to the industry professionals. I can for sure state that this research wouldn't have been possible without his active support. I would also like to thank the project participants: Elisa Brandts, Laurenz Kosichek, David Woo, Majid Shoraka, Manuel Archila and John Mackenzie who dedicated their time to be a part of this research during their busy schedule.

The financial support from Stantec – the industrial partner for this research, is deeply appreciated. Active support of construction firms like Ayo Smart Homes, Ellisdon and Rize Alliance Properties is also gratefully acknowledged.

Last but not least, I would like to specially thank my family and friends for their moral support and encouragement.

Dedication

To Mom & Dad

Chapter 1: Introduction

1.1 Background and Problem Statement

Effective capture of as-built information from construction project sites remains a significant challenge for all disciplines within the architecture, engineering, construction and operations (AECO) industry (Azhar 2011). As-built information is required to address a variety of project specific needs, including assessment of construction quality, and ensuring compliance to design requirements or capturing existing building conditions for planning upcoming renovations, or guiding future repairs during building operations. However, most of the required as-built information is still being captured through traditional practices such as the use of tape measure and 2D design drawings that are often time-consuming, labor-intensive, inefficient and prone to error, resulting in increased project delivery issues (Akinci et al. 2006; Gordon et al. 2003).

Stagnant profit margins and increasing competition from globalization are also forcing companies within the construction industry to constantly innovate and stay competitive. Leveraging innovative technologies is often crucial in making these companies more attractive to prospective clients either by helping in differentiating themselves from their competitors or by improving their current process efficiencies. One example where companies are leveraging such innovative technologies is the adoption and use of Building Information Modelling (BIM) across different project phases. With the use of advanced computational design methods, such as BIM designers are able to develop more complex architectural concepts nowadays (Eastman et al. 2011). BIM is also being used increasingly during construction phase to improve design coordination and identify construction schedule feasibility issues through clash detection tests and 4D simulation analysis (Eastman et al. 2011). Also, now there is an increased interest among the researchers, industry professionals and owners for adopting BIM during facilities management stage (Becerik-Gerber et al. 2011; Eastman et al. 2011). However, the use of BIM and other latest technological advancements for capturing and analyzing the required as-built information is still very limited among the practicing professionals. Most of this can be attributed to the lack of understanding on how and when BIM and other latest technological advancements can be leveraged for addressing various industry needs (Gu and London 2010). These issues and challenges have resulted in an increased interest among both researchers and industry professionals to investigate alternative approaches for effective and efficient capture of as-built information. Such improvements can not only be achieved by studying and understanding how BIM can be used for improving the current state of as-built information capture, but significant progress can also be made by leveraging and adapting the latest technological advancements from other industries that are best suited to address the current construction industry needs (Azhar 2011; Bryde et al. 2013; Eastman et al. 2011).

Several research groups have identified the above-mentioned limitations and investigated various as-built data capture technologies for tackling these issues, such as 3D Laser scanning, photogrammetry and interactive visual documentation (Bhatla et al. 2012; Gordon et al. 2003; Rankohi 2014). Such emerging technologies capture as-built data either in the form of 3D as-built models or 2D images that are then post-processed and analyzed using relevant BIM information. However, each of these approaches suffer from critical shortcomings, including the lack of affordability, the requirement for expertise to use, and the reliance on time-intensive intermediate steps (Volk et al. 2014; Zhu and Brilakis 2009), which limit their wide scale adoption within the construction industry. As a result, project owners and personnel are often forced to rely on traditional practices as opposed to using these emerging capture technologies. Hence, there is a critical need to find alternative technologies that are cost effective, easy to use and efficient in capturing the required as-built information.

This need for better alternatives led to the rapid development of various new model and image-based as-built capture technologies, such as mobile laser scanning; drone scanning, and spherical imaging, focused on addressing some of the above-mentioned drawbacks. However, with such new technologies now being developed at a rapid pace, there is an increased confusion among industry professionals to identify the best suitable capture technology which can address their specific needs. Hence, there is a need for developing a structured assessment framework that can enable the end user to conduct a rigorous comparison of different capture technology options. The assessment framework would help project teams to make informed decisions on the most suitable capture technology to address their project specific needs. The framework would also help in assessing the potential of any new capture technology to replace the current traditional practices. Such a structured assessment can also aid in identifying the use case scenarios where such new capture technology will be of utmost use.

1.2 Research Objectives

Several researchers have developed structured approaches to help end users identify the most appropriate capture technology (Zhu and Brilakis 2009), however, these were not developed based on an in-depth study of industry requirements. To address this research gap, the study focuses on developing a framework to assess the potential of any new capture technology for addressing different use case scenarios based on key industry requirements. Hence, this study aims to

1. Develop a framework for assessing the potential of new as-built information capture technologies to support construction purposes.

2. Assess the potential of two new capture technologies, mobile laser scanning and spherical imaging, using the developed framework.

1.3 Research Methodology

As part of the research methodology, four major research steps are devised to develop the required assessment framework and then implement it to evaluate the potential of two new capture technologies. The necessary details of these four major steps are summarized here.

i. Study and analyze different construction projects and use case scenarios:

A case study based approach was chosen for this research, and four different construction projects spanning across Vancouver, Canada were first chosen as sample case studies for this work. The relevant use case scenarios that require capturing of as-built information were first identified in this step. The project team members who are responsible for handling the as-built information aspects within these case study projects are also identified in this step. Then the current industry practices for capturing the necessary as-built information to address these identified use case scenarios were observed and analyzed. Thus, an in-depth understanding of different use case scenarios that require as-built information to be captured from project sites is obtained.

ii. Identifying the key industry requirements:

In this step, an in-depth industry requirement analysis is conducted with the support of various industry professionals identified from the earlier step. Through this analysis, the key requirements that govern the usage of any new technology to capture the required as-built information for all the observed use case scenarios were identified. Such data is collected through a series of informal discussions with the various project team members as part of this step.

iii. Developing the assessment framework:

This step then focuses on developing the assessment framework based on the key industry requirements from the earlier step. The assessment methods and the possible benchmarks for comparison are identified in this step so as to develop the final assessment framework. The intent was to develop a framework which can then be used to assess the potential of any new capture technology across the identified use case scenarios.

iv. Devising appropriate framework implementation approaches:

Finally, this step focuses on developing appropriate framework implementation approaches to test both the mobile laser scanning and spherical imaging technologies. Appropriate benchmarks and assessment methods for each capture technology were identified in this step. These assessment approaches were then used to conduct an in-depth assessment of both the technologies by testing them on relevant case studies. The benefits and limitations of these new capture tools were then identified.

1.4 Thesis Outline

In this thesis, a review of the latest research developments related to the current existing technologies is first presented in Chapter 2. The details of the research methodology employed for studying the current industry practices to capture the required as-built information are then presented in Chapter 3. The steps followed for developing and implementing the developed framework to assess the potential of two new capture technologies is also presented in this chapter. The major observations from studying and analyzing the current industry needs and practices for capturing the required as-built information are then presented in Chapter 4. The assessment framework developed by conducting an in-depth industry requirement analysis is then followed in Chapter 5. The benefits and limitations that are observed from testing the two new capture tools to address relevant use case scenarios are then summarized and discussed in Chapter 6 and Chapter 7. Finally, the conclusion section where the key findings of this research are summarized and some of the major limitations with this research work are highlighted is provided in Chapter 8.

Chapter 2: Research Background

This chapter focuses on providing key insights into the current state of the art with regards to as-built information capture and helps the readers to gain some insights into other research works addressing similar issues. A review of the latest research developments related to the current existing technologies is first presented in the chapter. Then a review of relevant works where the researchers focused on conducting a structured comparison of different technologies is presented. Some of the new technology advancements and the research works which focused on testing such new technologies are then discussed in the final section.

2.1 Current State of As-Built Information Capture

Although many companies have invested heavily to reap the full benefits from the use of Building Information Modelling (BIM), its usage is rather found to be predominant only in the project design phase (Azhar 2011; Eastman et al. 2011). The limited use of BIM in other application areas such the analysis of the captured as-built information using BIM is resulting in the loss of efficiencies which can otherwise be obtained from the full use of BIM (Hill 2014). Most of this can be attributed to the lack of understanding on how and when BIM can be leveraged for addressing various industry needs in conjunction with the use of other latest technological advancements (Gu and London 2010). In order to address this, researchers have long been working on developing various technologies (both model-based and image-based) to better capture the required as-built information and then incorporate the use of BIM into analyzing the captured as-built information. Laser scanning; photogrammetry and drone scanning (Bae et al. 2013; Golparvar-Fard et al. 2009; Volk et al. 2014) are some of the latest model-based capture technologies that have been in focus lately to improve the current state of as-built information capture. All the above-listed capture technologies focus on capturing the surrounding as-built conditions in the form of 3D as-built models, although the exact procedure to generate the final as-built model varies (Arayici 2008; Klein et al. 2012) which are then analyzed by comparing with the design BIM models.

Laser scanning, for example, focuses on generating a 3D point cloud of the surrounding conditions through time-of-flight technique to record the coordinate data of various points spread across large areas. This data is then used to generate a 3D as-built model (Arayici 2008; Son et al. 2015; Tang et al. 2010). Its ability to collect huge amounts of data in a short period of time makes this quite suitable for large scale and infrastructure projects (Zhu and Brilakis 2009). In contrast, photogrammetry is an image-based technology that captures surrounding conditions in a series of 2D images which are then processed extensively using a technique called triangulation to produce the final 3D point cloud (Bhatla et al. 2012; Klein et al. 2012; Zhu and Brilakis 2009). Recently, researchers have also focused on using drones to capture as-built data in the form of 3D point clouds either by fixing a light detection and ranging (LiDAR) scanner to the drone (Wang et al. 2015) or by capturing a series of 2D images which are then analyzed to generate 3D point clouds (Ham et al. 2016). All these capture technologies have been developed to address specific problems either with other capture technologies or with traditional practices. Photogrammetry, for instance, was developed as an alternative to laser scanning in order to address some of its limitations including low mobility and high cost (GSA 2009; Volk et al. 2014; Woo et al. 2010). Drone scanning was researched as an alternative to capture as-built data in inaccessible areas or regions that are difficult to capture using any of the other capture technologies (Ham et al. 2016; Wang et al. 2015). All the technologies that capture the required as-built data in the form of 3D as-built models are categorized as model-based capture technologies in this study.

Some researchers have also looked into assessing the suitability of using latest capture tools such as laser scanning to address some of the industry needs like construction quality assessment using BIM (Akinci et al. 2006; Bosché 2010; Gordon et al. 2003). However, certain practical limitations such as high investment cost (laser scanning) (Volk et al. 2014); time intensive steps (photogrammetry) (Klein et al. 2012; Zhu and Brilakis 2009); regulatory restrictions (drone scanning) and required expertise to use (laser, drone scanning) (Ham et al. 2016; Volk et al. 2014) have restricted their adoption within the construction industry on a broader scale even though they are suitable to address some of the current issues. Hence, researchers are now focusing on finding alternative methods to address some of the above-mentioned issues.

2.2 Assessment Framework and Comparison of Various Capture Technologies

Although most of the research related to as-built information capture is focused on the technological aspects, few researchers have also worked on conducting a structured comparison of various capture technologies that are already available in the market. For instance, (Zhu and Brilakis 2009) have conducted an in-depth study on the comparison of various optical based as-built data capture techniques based on metrics proposed by NIST (NIST 2006). However, these comparison metrics do not capture all the requirements of the industry professionals that influence the adoption of any new capture technology. Thus, a framework is to be developed based on an in-depth industry requirement study so as to identify other missing metrics necessary for conducting a structured assessment of any new capture technology from construction industry perspective.

2.3 Latest Advancements in As-Built Information Capturing Technologies

Besides the above-mentioned areas of research, researchers have also looked into assessing the usability of several new technologies that are suitable for capturing as-built information. Researchers (Bhatla et al. 2012) for example, looked into the evaluation of using handheld digital cameras to capture surrounding as-built conditions in the form of 3D as-built models. Also, some research works (Rankohi 2014) explored the potential of using panorama images to effectively track construction progress on project sites remotely. Besides the researchers, industry professionals have also developed new technologies such as the interactive visual documentation to capture and document the exact built conditions during the construction stage. Such technologies that capture the required visual as-built data in the form of images (2D, panorama, spherical etc.) are categorized as image-based capture technologies in this study.

Thus, researchers and industry professionals have already explored several alternative capture technologies to address various issues faced by the industry. However, the adoption of such latest technologies to capture the required as-built information is still uncommon due to various reasons as explained earlier. In order to address this, technology developers and researchers have been actively looking into other alternatives. Two such alternative technologies that piqued the interest of both the researchers and industry professionals lately are: mobile laser scanning (model-based) and spherical imaging (image-based) technologies.

Mobile laser scanning relies on using a mobile tablet device as shown in Figure 2.1 (a) to capture the as-built conditions in the form of 3D as-built models (thus making it a model-based capture technology). The spatial data is captured through inbuilt depth sensors by reading the reflected infrared lights using the device's infrared camera (Kalyan et al. 2016). Whereas, spherical imaging technology relies on using special camera devices to capture the surrounding as-built conditions in the form of spherical images (thus making it an image-based capture technology). For this, the camera uses two 180^0 fisheye lenses to capture the surrounding conditions in one click as shown in Figure 2.1 (b), opposed to the traditional approach where normal 2D images are to be taken in all the six directions from a given location which are then processed to generate the final spherical image. It is because of these user convenience factors that these technologies have piqued the interest of both the researchers and industry professionals as new alternative capture technologies.

However, there aren't many research works which focused on assessing the suitability of these two new capture technologies from construction industry perspective. Also, it is noticed that most of the optical and image-based research have been focused on construction progress tracking application with a little focus on other application areas (Rankohi and Waugh 2014). Hence, this work focuses on assessing the suitability of these new capture technologies from construction industry perspective and also focuses on assessing the usability of spherical imaging technology across other application areas.

(a) (b)

Figure 2.1: (a) Latest mobile laser scanner - Project Tango (b) Latest Spherical Camera - Ricoh Theta S.

Chapter 3: Research Methodology

The research methodology employed in this study can be divided into four major steps as depicted in the research roadmap diagram given below. These steps represent the activities necessary for developing the required assessment framework and then implementing it to evaluate the potential of any new capture technology. The complete details of these steps are provided in the following sections.

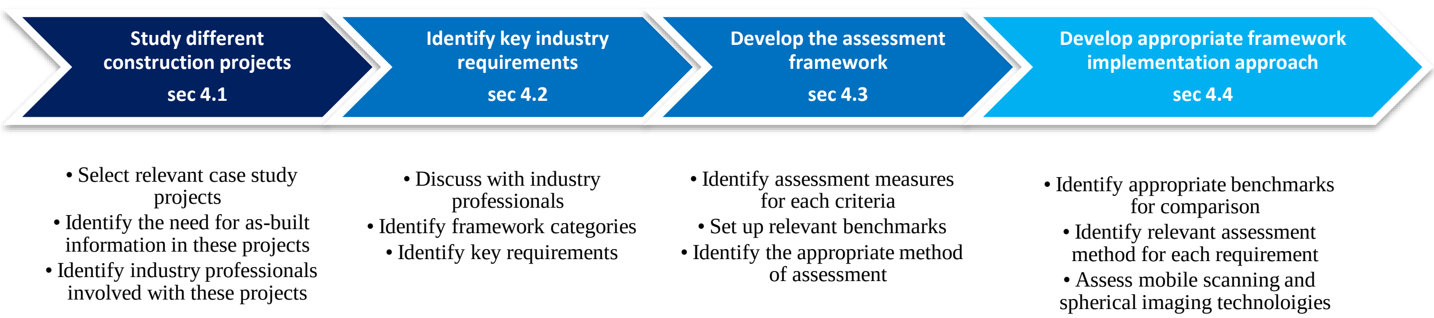


Figure 3.1: Research roadmap summarizing the methodology employed in this study

3.1 Study and Analyze Different Construction Projects and Use Case Scenarios

The first step in this research focuses on studying different construction projects. A case study based research approach is chosen for this study due to its suitability for addressing industry-wide issues. Such an approach focuses on a collaborative effort between academia and industry practitioners so as to capture and address the real world issues (Rowley 2002; Yin 2012). For this, four different construction projects spanning across Vancouver, Canada were chosen as sample case studies for this work. The project teams from the respective design and contracting firms involved with these projects are required to capture some sort of as-built information to address their various needs. The relevant details about the case study projects and the respective project team members who were involved in this study are provided in the description below.

1. **<u>Ayo Smart Home:</u>** The Ayo Smart Home project is a small-scale affordable housing project as shown in Figure 3.2 where the project team aims to provide housing solutions for the low-income sector while maintaining high levels of livability and energy efficiency. For this purpose, a small-scale pilot home is built on the UBC Vancouver campus, and the project team wished to ensure that all the critical components are being built as per design requirements during the construction phase. Hence, during the construction it was often required to capture as-built information of such components in the form of measurement data. The project manager of this project was involved in this study to provide inputs on current industry requirements with respect to the use of any new capture technology suitable for addressing this use case.

Figure 3.2: Sample Project Rendering - Ayo Smart Home. (Courtesy of Ayo)

2. **Cadillac Fairview Shopping Mall:** This is a small-scale store upgradation project, where future renovation work is planned for one of the stores located within the Cadillac Fairview Shopping Mall in downtown Vancouver, British Columbia. The project team intends to capture the current as-built conditions of the store so as to plan and develop a suitable design for future renovation work. For this, both visual and spatial as-built information in the form of dimensional measurements were to be captured. The project architect and designer of this project were involved in this study to provide inputs on the industry requirements for using any new capture technology to address this use case.

Figure 3.3: Sample Project Rendering - Cadillac Fairview Shopping Mall (Courtesy of Stantec)

3. Brentwood Town Centre: This is a large scale mixed development project that includes the construction of a 3-story shopping Centre and several residential high-rise towers along with six levels of below grade parking as shown in Figure 3.4. The project is located in the heart of Burnaby city with a total project budget of $1 billion approximately. Owing to the project's large scale, huge numbers of project participants are involved in the project delivery working from different locations. Thus, the project team requires to conduct rough design compliance checks and ensure everything is built as per design requirements. For this, as-built information in the form of visual data is to be collected from project site during construction phase which is then shared with all the project team members. The principal architect, on-site architect, and project engineer were involved in this study. The senior project manager, on-site project coordinator of the contracting firm were also involved.

Figure 3.4: Sample Project Rendering - Brentwood Town Centre (Courtesy of Stantec)

4. Gold House High-rise: This is a residential and commercial high-rise construction project located in Burnaby city as shown in Figure 3.5. It is an owner build project where the project client’s team is directly involved in the project construction without any third party contracting firm. The project is currently in the construction phase and the project team is interested in having visual as-built documentation of exact built conditions during the construction phase. These visual documentations are then to be used for guiding future repair works during the operations phase of the commercial rental spaces. For this, exact built conditions on the project site are to be captured during construction. The site superintendent who is also the owner representative for this project was involved in this study for providing necessary inputs representative of current industry requirements.

Figure 3.5: Sample Project Rendering - Gold House High-rise. (Courtesy of Stantec, Rize Properties)

Once the case study projects are chosen, the research then focused on identifying the various use case scenarios where the industry professionals are required to capture as-built information from these project sites. While identifying these use case scenarios, the current industry practices followed by each project team is also studied. This is done through direct observations on project site by observing the respective project team members. The issues and problems faced by the industry practitioners due to the current practices are also noted. Identifying these inefficiencies and limitations allowed us to gain a better understanding of the dominant issues that are to be addressed through new capture technologies. Studying the current industry practices also helped in identifying the type of as-built information that needs to be captured so as to address each use case scenario. Thus, an overall picture of the current situation is obtained.

3.2 Identify Key Industry Requirements

After identifying the use case scenarios, a requirement analysis is conducted with the support of various industry professionals involved in this study. Such an analysis is necessary for identifying the important parameters that govern the usage of any new technology to address the above identified use case scenarios. For this, besides analyzing the current industry needs and practices to address the identified use case scenarios the study also focused on collecting more qualitative data through a series of informal discussions with the various project team members involved in addressing the identified use-case scenarios within the chosen case study projects. Besides the project specific team members, repeated informal discussions are also held with senior level management people such as the regional business leader; regional BIM lead and regional BIM manager within the corresponding design and contracting firms. This is to ensure that the developed framework indeed captures the industry requirements from all perspectives. Thus, an in-depth analysis of the current industry needs and informal discussions with varied industry professionals helped the research team to identify the major industry requirements.

3.3 Develop the Assessment Framework

After the key industry requirements are identified, appropriate assessment measures are then laid out for each requirement identified earlier. These assessment measures help the end user to better understand the actual assessment criteria for each requirement. Identification of these assessment measures is again based on informal discussions with relevant industry professionals. After determining the appropriate assessment measures, the comparison benchmarks are then setup. The performance of the proposed capture technology as per the chosen requirement criteria is to be compared against these benchmarks. The comparison with these benchmarks is then conducted by following an appropriate assessment technique. The identification of these comparison benchmarks and assessment techniques was based on the discussions with industry professionals as well as the previous works done by some researchers (Bhatla et al. 2012; Rankohi 2014; Tang et al. 2011) who focused on assessing various capture technologies using different assessment methodologies. Thus, a framework was finally developed by analyzing the industry needs with respect to different use case scenarios identified in this study. This framework can then be used to assess the potential of any new capture technology to address these use case scenarios.

3.4 Devise Appropriate Framework Implementation Approaches to Assess the Two New Capture Technologies

Once the assessment framework is developed, appropriate implementation approaches are then devised to assess the potential of two new capture technologies – mobile laser scanning and spherical imaging. For this, appropriate comparison benchmarks (among the three different options: 3D design models or 2D drawings or current practice) and relevant assessment methods were identified for each technology depending on the available data sources. The relevant industry professionals are also identified to gather feedback as part of the qualitative assessment methods. These framework implementation approaches were then utilized to evaluate the potential of these new capture technologies by testing their suitability to address relevant use case scenarios listed in Chapter 4. The benefits and drawbacks of these capture technologies were then identified using the developed implementation approaches.

Chapter 4: Analysis of Current Industry Needs and Practices

The motivation for this research is based on the analysis of the current industry needs and observation of their current practices through direct observations on various case study projects listed in section 3.1. This chapter discusses the need for as-built information and highlights the different use case scenarios where such as-built information is required. The chapter also highlights the different issues observed with the use of current practices for capturing the required as-built information to address all the different use case scenarios.

4.1 Use Case 1 – Construction Quality Assessment

While studying the Ayo Smart Home project, it was found that contractors are required to capture as-built information of the construction site conditions for conducting various activities, such as quality control activities or construction progress tracking. Capturing such as-built information is often crucial to prevent additional costs from late recognition of critical issues that must be addressed in the field. In the current process, it was observed that the project team conducts periodic site visits to verify the dimensional accuracy of critical components like parking level elevations. The accuracy of the built conditions is assessed by manually comparing the dimensions with the corresponding design specified values at different locations that are chosen randomly using 2D design drawings and tape measure as highlighted in Figure 4.1 (a), (b). This process was found to be time-consuming and highly prone to human error depending on the area and complexity of built conditions that are to be assessed.

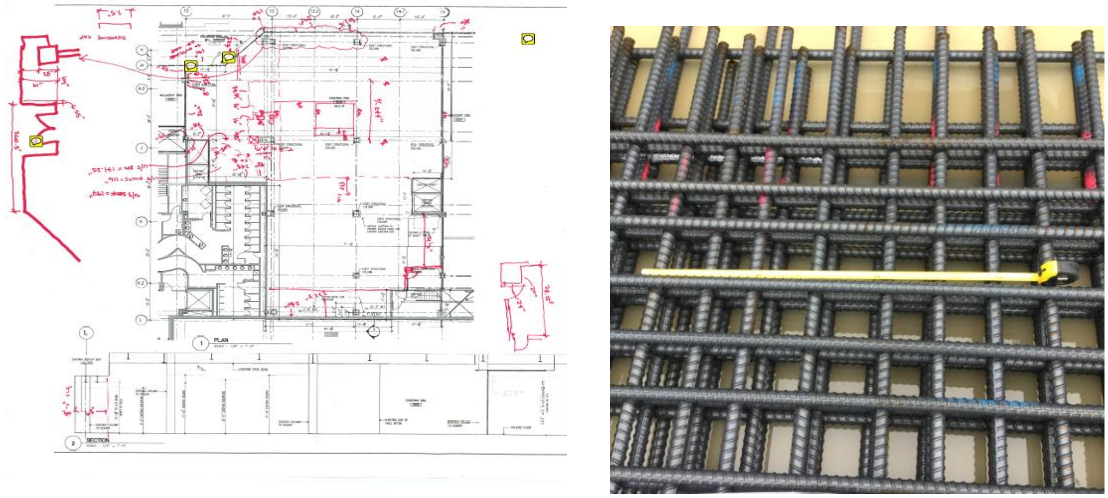
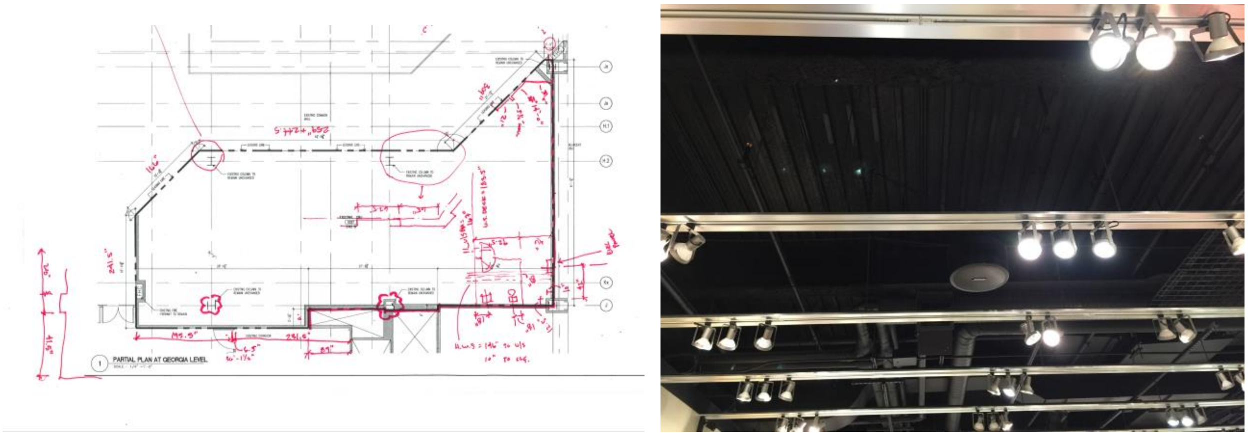


Figure 4.1: Sample images highlighting the current approach for conducting construction quality assessment of critical built components using 2D drawings and tape measure.

4.2 Use Case 2 - Capturing Existing Building Conditions to Plan Upcoming Renovations

While observing the Cadillac Fairview case study, it was found that designers are often in need of accurate as-built information of existing building conditions to plan for upcoming renovations design. As-built information in the form of measurement and spatial data is required by the project team members to generate accurate designs. However, this information is usually captured through manual techniques such as using a tape measure. This information is then analyzed through red line marking on existing old design drawings (if they exist) to identify discrepancies as shown in Figure 4.2 (a). This process is again found to be tedious, time consuming and prone to error. The measurement data of some components is often missing forcing the project team to revisit the site. The project team is also required to capture the current built conditions visually through a series of 2D images from different locations on the project site as shown in Figure 4.2 (b). However, these images are often not tagged with the corresponding location details thus making it difficult to analyze them later



(a) (b)

Figure 4.2: (a) Sample image highlighting the current red line marking approach to capture and verify the spatial information of current existing buildings. (b) Sample image highlighting how the current ceiling conditions are being captured using 2D images for future reference

4.3 Use Case 3 – Design Compliance Reviews

While studying the Brentwood town centre case study, it was noted that designers are also required to capture as-built information from the construction site for conducting rough design compliance checks to ensure everything is being built as per design specifications. In the current process, the project team conducts periodic site visits by traveling to the project site, visually inspecting the specific elements, and capturing any deviations using 2D images as shown in Figure 4.3 (a). The deficiencies are then communicated to other team members through site deficiency reports and annotated images as shown in Figure 4.3 (b). This process is noted to be very time-consuming and in some cases, the design consultants are forced to visit the site even for small checks. Although it was observed that the contractors were requested to send images for these small checks, it was noted that these images were not suitable for conducting such remote reviews in many cases. This current procedure where the project team members have to travel can also be expensive when the design team members are working from another location/city and they have to be flown in for conducting periodic site reviews.

(a) (b)

Figure 4.3: (a) Sample image showcasing the current design compliance review process where the project team is present on-site to capture any deficiencies as shown. (b) Identified deficiencies are annotated and highlighted to communicate the issue with other project team members.

4.4 Use Case 4 – Capturing the Exact Built Conditions during Construction

While studying the last case study – Gold house high rise, it was observed that owners and facility operators also require as-built information to capture the exact built conditions during the construction stage (Jung et al. 2014). Such information is necessary for guiding future repair works during the operations/facilities management stage. For this process, 2D images are taken from the project site before key enclosure activities such as concrete pours in slabs or closures of walls and ceilings happen. However, it was observed that the construction firms sometimes hire a third-party firm to take these images which are then tagged onto the respective floor plans for quickly navigating between these images as shown in Figure 4.4. Hiring such a third-party firm is dependent on various aspects like the project budget, availability of such services, project head being interested in such an approach. If a third-party firm is not hired in a particular project it is reported that the construction team takes some project images whenever possible which are then shared with the owners. However, this process is found to be inefficient since the content is often not tagged or organized thus making it difficult for future users to rely on this information. Also, the current process followed by the third-party firms is found to be time-consuming and ineffective in a few instances due to the large number of 2D images that should be taken to effectively capture all the surrounding as-built conditions.

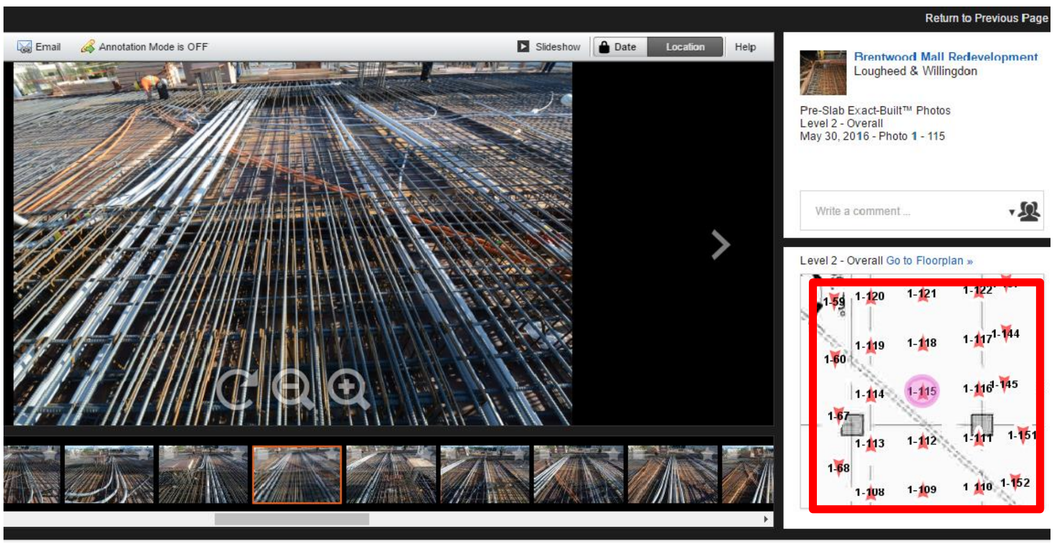


Figure 4.4: The current visual documentation approach used for capturing the exact built conditions during the construction stage in certain projects. The images are tagged onto the floor plans as highlighted.

Through these direct observations on various project sites, it was evident that as-built information is often required across different project phases. However, the type of information required is dependent on the user specific need and the intended use of such information as described earlier. Currently, the required as-built data can be categorized into two types: 1. Visual data that captures the visual information of the project site conditions; 2. Measurement data that captures the spatial information of the various built components on the project site. Thus, the type of as-built data that needs to be captured can either be visual or measurement/spatial information depending on the intended use. Through these direct observations, it was also determined that as-built information was critical for industry professionals in these four major scenarios. These major observations are summarized in Table 4.1 given below.

Table 4.1: Identified use-case scenarios where as-built information is to be captured from project sites.

S.No	Different uses for as-built information	Project Phase	Type of as-built data required
1	To conduct construction quality assessment for ensuring dimensional accuracy of critical built components	Construction	Measurement
2	To capture as-built conditions of existing buildings to plan the designs for upcoming renovation works	Design	Visual, Measurement
3	To conduct design compliance checks for ensuring everything is built as per design requirements	Construction	Visual
4	To capture the exact built conditions during construction for guiding future repair works during operations phase	Operations	Visual

Although, the project team members were aware of the latest capture technologies, such as laser scanning and digital photogrammetry, it was observed that they do not rely on such technologies on a daily basis. This was found to be due to several factors, including the high investment cost, the expertise required, the time intensive nature, and the slow adoption rate within the construction industry to try new technologies. Thus, the existing latest capture technologies are only considered when there is a definitive need that justifies the significant investment required for using them. These restrictions often force the project team members to rely on traditional methods. Hence, the need for alternative technologies that are suitable for capturing the required as-built information is clearly noted.

Chapter 5: Assessment Framework to Evaluate New Capture Technologies

Once the research methodology for developing the assessment framework is devised, the study then focused on its development. This chapter provides the details about relevant findings such as the key industry requirements, assessment measures and appropriate assessment techniques for each requirement. The chapter also provides the details about the framework implementation approaches devised for assessing the two new capture technologies. All these details are provided in the following sections.

5.1 Key Industry Requirements

After the major use case scenarios are identified as described in the earlier chapter, the study then focused on identifying the key industry requirements that govern the adoption of any capture technology based on the methodology described in Chapter 3. By observing and studying the current industry practices to address the various identified use case scenarios and by having a series of informal discussions with various industry professionals it is found that the use of any new capture technology within a design and contracting firms is influenced by a set of key requirements. These requirements can be divided into three major categories as described here:

1. User Requirements: These requirements are identified based on the discussions with industry professionals such as the on-site architect and project coordinator who are the actual technology users. They are responsible for capturing the required as-built information from project sites. Through the informal discussions with them it was identified that their major requirements focused mainly on user convenience factors such as the existence of software support for analyzing data; ease of use and mobility of capture device, since most of the use case scenarios listed in Table 4.1 are to be addressed frequently during the entire project duration. This set of requirements is found to be the key parameters that influence the adoption of any new capture technology from their perspective.

<u>2. Management Requirements:</u> These requirements are identified based on the informal discussions with industry professionals who are more involved in the managerial aspects of the entire firm such as the senior business leader; regional BIM lead and the regional BIM manager. Their requirements focused more on the cost and managerial aspects such as the device, software costs and the time required to train the end users who should use such technologies.

<u>3. Project Team Requirements:</u> Finally, this set of requirements is identified based on the discussions with senior project team members and project heads such as the principal architect; design engineers, senior project manager and site superintendent who are directly responsible for successful delivery of their respective construction project. Their requirements focused majorly on the aspects such as the quality and suitability of captured data; ability to share the data among project team members; time required to capture and analyze data and the impact of weather conditions for capturing as-built information. It can be deduced that the smooth functioning of the whole project team is the major criteria for them, thus their requirements focused mainly on such aspects which can influence the smooth functioning of the entire project team.

Thus, the key industry requirements which govern the adoption of any new capture technology are identified.

5.2 Assessment Framework

After the identification of key industry requirements, appropriate assessment measures for each of them were set up based on the methodology described in section 3.3. These assessment measures are simple research questions such as "*Is the capture technology easy to use?" or "Is the captured data accurate and suitable to meet the industry standards and needs?"* which are necessary for guiding the end users to conduct a more structured assessment based on the developed framework. Then appropriate comparison benchmarks were also identified. It is found that these benchmarks can be anything such as the performance of the current practice or the available 3D design models or the 2D design drawings depending on the data available for conducting such comparisons. The assessment techniques for evaluating the potential of any new capture technology based on each requirement were then established. The comparison with the identified benchmarks is conducted by following these assessment techniques. The assessment technique can either be qualitative testing approach or direct testing approach.

The qualitative testing approach includes techniques such as conducting informal discussions with respective industry professionals or organizing product demos to gather feedback from potential users. It can also include techniques such as conducting product reviews and product research to identify some of the necessary information. Whereas, the direct testing approach includes techniques such as testing the proposed capture technology on different case study projects to evaluate its performance. The choice of assessment technique is influenced by both the comparison benchmark and the underlying industry requirement. Table 5.1 provides a summary of the assessment framework developed to evaluate the potential of any new capture technology. The framework includes appropriate benchmarks, assessment measures and assessment techniques for each industry requirement, as shown in Table 5.1.

Table 5.1: Assessment framework developed for evaluating the potential of new as-built information capture technologies.

Category	Requirement to be assessed	Assessment Measure	Appropriate benchmark to compare with	Type of Assessment Technique
User Requirements	*1. Necessary Software Support*	*Is there any software available which can be used to process and analyze the captured data as per industry practitioner needs? (yes or no)*	-----	*Qualitative testing (conducting product reviews and research)*
	2. Ease of use	*Is the capture technology easy to use?*	*Current traditional practice (How does it compare with the current practice?)*	*Qualitative testing (informal discussions and feedback from relevant industry professionals)*
	3. Mobility	*Is it convenient to carry the device across the project site? (yes or no)*	-----	*Qualitative testing (informal discussions and feedback from relevant industry professionals)*
Management Requirements	*1. Device Cost*	*Is the device affordable?*	*Current traditional practice (How does it compare with the costs incurred from following the current practice?)*	*Qualitative testing (conducting product reviews and research)*
	2. Post-processing software cost	*Is the software necessary for analyzing the captured data affordable?*	*Current traditional practice (How does it compare with the costs incurred from following the current practice?)*	*Qualitative testing (conducting product reviews and research)*
	3. Training time	*How much time is needed to train the respective users in getting familiar with both the device and post-processing software?*	*Current traditional practice (How does it compare with the time required for training new project personnel to follow the current practice?)*	*Qualitative testing (informal discussions and feedback from relevant industry professionals)*

Table 5.1: Assessment framework developed for evaluating the potential of new as-built information capture technologies.

Category	Requirement to be assessed	Assessment Measure	Benchmark to compare with	Type of Assessment Method
Management Requirements	4. Contractual and Regulatory Restrictions	*Are there any contractual and regulatory restrictions that prevent the proposed capture technology from replacing the current traditional practice? (yes or no)*	-----	*Qualitative testing* *(informal discussions and feedback from relevant industry professionals)*
Project Team Requirements	1. Data accuracy and suitability	*Is the captured data accurate and suitable to meet the industry standards and needs?* *(Model dimensions, data completeness, quality are some of the parameters that are to be evaluated for this).*	*Design models or design drawings or direct measurements from project site or current traditional practice* *(How does the data compare with those specified in design models and drawings etc.)*	*Direct and qualitative testing* *(in-depth testing of the proposed capture technology on various sample case studies)*
	2. Data interoperability and sharing	*Is it easy to share the captured data across project team members and multiple software platforms? (yes or no)*	-----	*Direct testing* *(in-depth testing of the proposed capture technology on various sample case studies)*
	3. Time required to capture and analyze	*How long does it take to capture and process the data?*	*Current traditional practice* *(How does it compare with the time required for capturing and analyzing the as-built data as per the current practice?)*	*Direct testing* *(in-depth testing of the proposed capture technology on various sample case studies)*
	4. Weather conditions	*Do the outside weather conditions affect the data quality? (yes or no)*	-----	*Direct testing* *(in-depth testing of the proposed capture technology on various sample case studies)*

5.3 Framework Implementation Approaches

After the assessment framework is developed, the framework implementation approaches required for assessing the usability of both the model-based (mobile laser scanning) and image-based (spherical imaging) technologies were devised. Since the comparison benchmarks and the exact assessment techniques are hugely dependent on the type of data captured by the proposed capture technology two different implementation approaches were developed for each type of capture technology. The details of these implementation approaches are provided in this section.

5.3.1 Approach for Assessing Model-Based Capture Technologies

This approach consists of two major steps as listed here:

1. Assessing the technology as per the user and management requirements listed in the framework
2. Assessing the technology as per the project team requirements.

Since the assessment technique for user and management requirements (qualitative testing) is different from the one required for project team requirements (direct testing), it is decided to divide the assessment approach into two major steps. The direct testing for assessing as per the project team requirements further involves three major steps. The major details of these three steps are summarized in the form of a UML activity diagram as shown in Figure 5.1 for a quick overview. Further details are provided next.

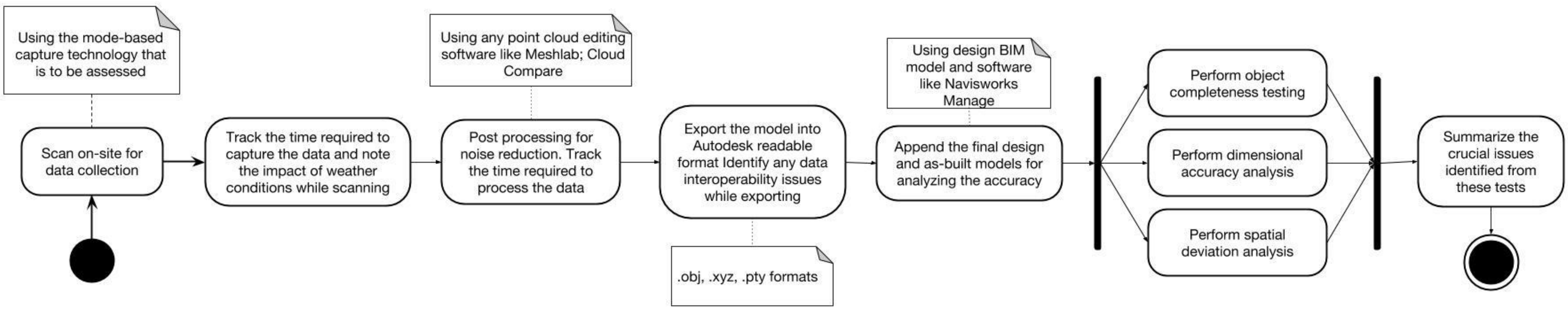


Figure 5.1: UML activity diagram summarizing the approach for assessing the project team requirements with respect to model based capture technologies.

5.3.1.1 User and Management Requirements

The first step in evaluating the potential of any model-based capture technology is its assessment as per the user and management requirements criteria listed in the developed framework. Researchers are often found focusing most of their efforts to address the technical challenges such as data accuracy, post-processing software development for new technologies, and usually neglect to understand how these new technologies are meeting the necessary user and management requirements. However, assessing the new technologies and checking if they address the major user and management requirements is also crucial.

Owing to the qualitative nature of the assessment tests for user and management requirements criteria, the model-based technology is assessed through a series of informal discussions with management personnel such as regional BIM managers and also through quick product demos to prospective users. The technology and product descriptions are also used as a guide to address certain industry requirements such device cost and post processing software cost. Thus, the model-based technologies are assessed as per the user and management requirements listed in the developed framework.

5.3.1.2 Project Team Requirements

The second step in evaluating the potential of any model-based capture technology is its assessment as per the project team requirements listed in the developed framework. However, assessing them as per these set of requirements needs in-depth testing on various case study projects as listed in the assessment technique. This section provides the details about the steps that are to be followed so as to assess any model-based technology as per the four project team requirements listed in the framework given in Table 5.1.

1. Data Collection: The first step constitutes of data collection where the on-site conditions are scanned and captured in the form of 3D meshed models or 3D point clouds using the proposed model-based capture technology. The exact steps for generating the required model can vary depending on the type of technology used for capturing. The time taken to capture the final 3D as-built model is also tracked in this step. The effect of outside weather conditions is also noted and studied during this data collection step.

2. Post-Processing: The second step then constitutes of post-processing where the generated 3D as-built model is refined so as to make it suitable for conducting data analysis. The model is refined using various noise reduction techniques like vertex removal and other filtering methods. Most of these features are available in many open source mesh editing software such as MeshLab, Cloud Compare etc {Citation}. Once the refined model is generated, it is then tried to export the data into an Autodesk readable format since most of the Industry practitioners are mainly relying on Autodesk products like Recap, Revit and Navisworks. This test ensures that the captured data is indeed interoperable and easy to share as stated in the project team requirements of the developed framework. The time required to process the captured data is also tracked in this step.

3. Data Analysis: This step involves evaluating the model accuracy through a series of three comparison tests described below. For this, the existing design model or 2D drawings are to be used for comparison against the generated 3D as-built model

i. *Object Completeness Testing:* In this test, the 3D as-built model is first compared with design models or 2D drawings to assess if the model-based technology captured all the surrounding objects. For this, the design and the 3D as-built models are appended in any comparison software such as Navisworks to identify any missing objects. In order to identify the missing objects, color coding, and transparency techniques are used.

ii. *Dimensional accuracy analysis:* This test involves measuring the dimensions of various objects recorded in the 3D as-built models. These dimension values are then compared against the benchmark values obtained through manual tape measure directly on the project site. The absolute difference between these values is recorded for estimating the accuracy levels. Thus, this test helps in establishing the accuracy level of the generated 3D as-built models. Previous work done by other researchers (Bhatla et al. 2012) provided a guide for developing the methodology to perform this analysis.

iii. *Spatial Deviation analysis:* This test tries to evaluate the spatial accuracy of the 3D as-built model by identifying spatial deviations like orientation changes, deviations in object location etc. This is based on some previous research work (Tang et al. 2011) where the deviations were identified through color coding and manual checks.

Thus, a framework implementation approach to assess the potential of model-based capture technologies is devised which was then used to test the mobile laser scanning technology as part of this study.

5.3.2 Approach for Assessing Image-Based Capture Technologies

This assessment approach also consists of two steps similar to those described for model based capture technologies.

5.3.2.1 User and Management Requirements

The first step in evaluating the potential of any image-based capture technology is its assessment as per the user and management requirements criteria listed in the developed framework. The assessment methodology is similar to the one employed for assessing model-based capture technologies as described in Section 5.3.1.1. Thus, both the user and management requirement aspects are assessed through product demos to potential users and informal discussions with respective industry professionals such as the regional BIM managers.

5.3.2.2 Project Team Requirements

The second step in evaluating the potential of any image-based capture technology is its assessment as per the project team requirements criteria listed in the developed framework. However, this requires in-depth testing on various case study projects. The details about the necessary steps that are to be followed are provided in this section. The major details of these steps are also summarized in the form of a UML activity diagram as shown in Figure 5.2 for a quick overview.

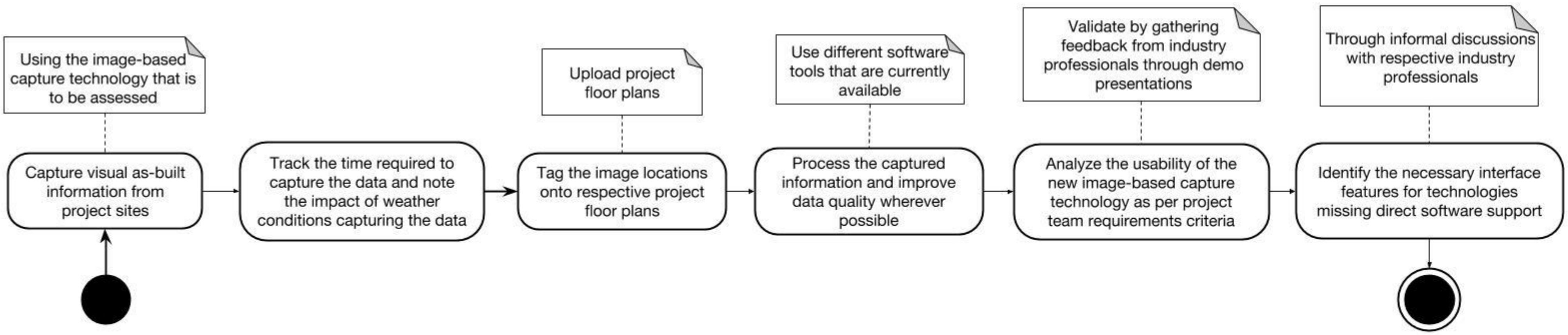


Figure 5.2: UML activity diagram summarizing the approach for assessing the project team requirements with respect to image-based capture technologies.

1. Data Collection:

Periodic site visits are conducted to capture the required visual as-built information from the project site using the image-based capture technology. The image locations and the time required to capture the necessary information are also noted. The effect of outside weather conditions is also noted and studied during this data collection step.

2. Post-Processing: The second step then constitutes of data processing where the captured visual as-built information is analyzed. The information is first edited to improve the final quality when necessary. Then different software tools like Roundme, MS Paint are used to process and analyze the images. The time required to analyze the data is also tracked in this step. Any interoperability issues are also identified while conducting the post processing on the captured data.

3. Data Analysis: The last step then involves analyzing the extent to which such image-based technologies are indeed addressing the required industry needs. Owing to the qualitative nature of the captured data, the sample results are presented to project team members and other senior management people such as the regional BIM manager; the principal architect and the senior project manager. The limitations like data accuracy and suitability issues were then identified based on the feedback received from them.

While conducting this data suitability testing, an interface feature identification step is also conducted. The use of such latest image-based technologies has gained a lot of attention only recently. Most of the research and investment from industry companies has already occurred in model-based capture technologies but not much in these image based technologies. Due to this, there is currently no off the shelf software solution available that can support the use of the latest image-based technologies. Thus, the necessary interface features that are to be included in any future software that is to be developed for addressing any of these use case scenarios is also identified. Such information was collected through a series of informal discussions with varied industry professionals such as the regional BIM managers and project team leads like the principal architect, the senior project manager, and the site superintendent of the respective case study projects. Demo presentations highlighting the various possible interface features are used for guiding these discussions. The feedback from these industry professionals is then noted to identify these essential features.

Chapter 6: Framework Implementation Findings

Once the framework implementation approaches were devised, they were then utilized to assess the potential of two new capture technologies i.e. mobile laser scanning (model based) and spherical imaging (image based) - to address the different use case scenarios listed in Table 6.1. The mobile laser scanning technology is tested to capture the required as-built data in two major use case scenarios: Construction quality assessment and the capture of the existing building conditions to plan upcoming renovation design. Whereas, the spherical imaging technology is tested to capture the required as-built data in the other two major use case scenarios: Design compliance reviews and the capture of exact built conditions during construction. For this, the technologies are first assessed as per the user and management requirements identified in the developed framework by following the implementation approach laid out in section 5.3.1.1. Then, the technologies are assessed as per the project team requirements by following the implementation approach laid out in sections 5.3.1.2 and 5.3.2.2. Since this assessment requires direct testing of the proposed technologies on various project sites, relevant case study projects are chosen for directly testing the potential of both the technologies to address each use case scenario. The necessary details are summarized in Table 6.1 for quick reference.

Table 6.1: Relevant use case scenarios identified for assessing the potential of two new capture technologies chosen in this work.

S.No	Scenario tested	Technology assessed	Case Study
1	To conduct construction quality assessment of critical built components using 3D as-built models.	Mobile Laser Scanning	*Ayo Smart Home*
2	To capture as-built conditions of existing buildings in the form of 3D as-built models so as to plan the upcoming renovation design	Mobile Laser Scanning	*Cadillac Fairview Shopping Mall*
3	To conduct design compliance reviews remotely using spherical images	Spherical Imaging	*Brentwood Town Centre*
4	To conduct visual as-built documentation of exact built conditions during construction using spherical images	Spherical Imaging	*Gold house high-rise*

6.1 Assessing the New Technologies as per the User and Management Requirements

For this assessment, a series of short informal discussions and product demos with both the technology users and senior level management personnel are conducted. Through these interactions, it is found that both the proposed capture technologies satisfy the general user and management requirements in all the considered use case scenarios. The industry professionals are comfortable with the level of ease and the costs involved in using these technologies. However, it has been found that several contractual and regulatory restrictions can hinder the usability of spherical imaging technology to conduct remote deficiency reviews. These relevant findings are summarized in Table 6.2 so as to provide a quick overview of the assessment results as per the user and management requirement categories. Thus, the potential of mobile laser scanning and spherical imaging to address the considered use case scenarios is first assessed with respect to the user and management requirements.

Table 6.2: A summary of the assessment results with respect to the user and management requirements listed in the developed framework.

Category	Requirement to be assessed	Model-based capture technology	Image-based capture technology
		Mobile Laser Scanning	*Spherical Imaging*
User Requirements	*1. Necessary Software Support*	Open source software like Meshlab are present which can be used for analyzing the captured 3D as-built models	Set of image editing and spherical image hosting software are present which are to be used in parallel due to the lack of a single out-of-the-box software that can address all the needs of construction industry professionals
	2. Ease of use	Often easy to use with a minimal learning curve	Easy to use with negligible learning curve – process similar to taking normal photos
	3. Mobility	Highly mobile and convenient to carry around the site	Highly mobile and convenient to carry
Management Requirements	*1. Device Cost*	Affordable with a price tag of around 500-1000$	Affordable with a price tag ranging between 500-800$
	2. Post-processing software cost	The required software cost is minimal and is quite affordable	The required software cost is minimal and is quite affordable
	3. Training time	Requires some initial training to get the users familiar with the post processing software	Do not require any additional training. Quick demo of the device and software is enough for getting the users comfortable
	4. Contractual and Regulatory Restrictions	No observed contractual or regulatory requirements that can restrict its use in any of the applicable use case scenarios	Contractual and regulatory requirements like compulsory occasional field visits can restrict the use of spherical imaging for conducting remote deficiency reviews frequently. Whereas, no such requirements exist that restricts the use of spherical images for visual as-built documentation of exact built conditions

6.2 Assessing the New Technologies as per the Project Team Requirements

For this, both the technologies are assessed as per the four project team requirements identified during the framework development. These requirements are listed here again for quick reference:

1. Is the captured data accurate and suitable for addressing the respective use case scenarios?
2. Is the data interoperable among different software and is it easy to share the captured data among project team members?
3. What is the time required to capture and analyze the data?
4. What is the impact of weather and surrounding conditions on the captured data?

Since the assessment of both the technologies as per these requirements require direct testing on project sites, relevant case study projects are chosen as summarized in Table 6.1. The important findings and the necessary details are provided below

6.2.1 Mobile Laser Scanning

The mobile laser scanning technology is tested to capture the required as-built data in two major use case scenarios: Construction quality assessment and the capture of the existing building conditions to plan upcoming renovation design. In order to assess it’s potential to address these particular use case scenarios the technology is first assessed as per the user and management requirements. The results of this assessment were already presented in Table 6.2. After this, the technology is assessed as per the project team requirements by testing it on relevant case study projects. The study also focused on testing how the existing BIM models and design data can be leveraged to analyze the captured as-built data more effectively. This section provides the details of the important findings obtained from these tests.

6.2.1.1 Use Case 1 - 3D Construction Quality Assessment

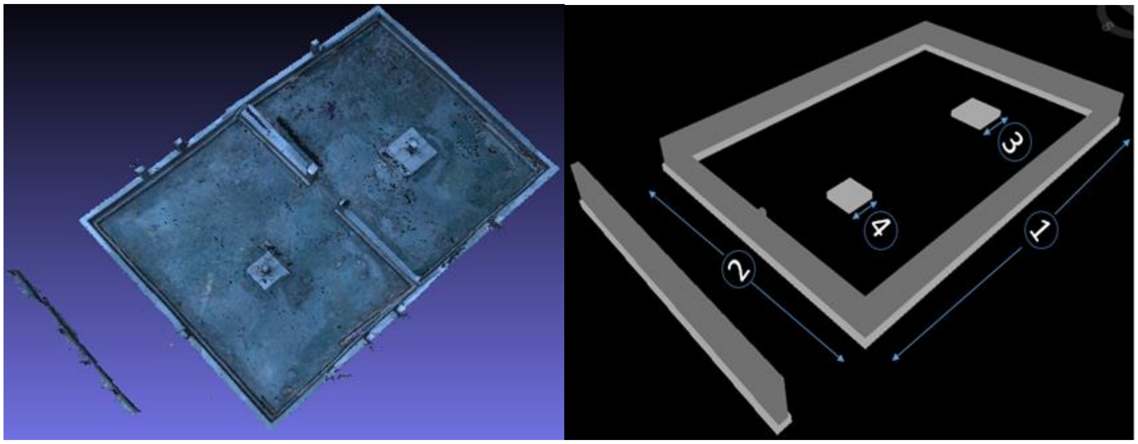
For testing the usability of mobile laser scanning to conduct construction quality assessment using 3D as-built models, Ayo smart home case study is chosen. Periodic site visits are conducted during the time of construction, to capture two different building components within the project. Two components were chosen so as to test the impact of different weather or surrounding conditions. The technology is then assessed as per the four project team requirements described earlier. To perform this assessment the steps laid out in section 5.3.1.2 were followed. The two building components that were selected are described below:

- *Foundation system:* This building component is chosen to validate the usage of mobile laser scanners in exterior environments. Testing on this component will provide the scope to assess the impact of surrounding weather conditions which is one of the project team requirements.
- *Interior hall:* To validate its usage in interior environments

1. Data Accuracy and Suitability Evaluation:

- **Foundation:**

i. *Dimensional Accuracy Analysis*: The generated 3D as-built model shown in Figure 6.1(a), is utilized for conducting the dimensional accuracy analysis. For this, the dimension values of various elements within the as-built model are compared with those obtained from on-site measurements. The components selected are indicated with a number as shown in the Figure 6.1(b). Table 6.3 shows the results of the accuracy analysis for this case.



(a) (b)

Figure 6.1: (a) As-built model generated using mobile laser scanner in exterior conditions; (b) 3D BIM model highlighting the components selected for dimensional accuracy testing.

Table 6.3: Dimensional accuracy analysis of the foundation 3D as-built model.

Component IDs as shown in Figure 6.1(b)	Measured dimensions from site (m)	Dimension value from as-built model (m)	Absolute Difference (Δ)
1	12.2	12	0.2
2	8.5	8.35	0.15
3	1.2	1.15	0.05
4	0.9	0.85	0.05
TOP OF FOOTING (Depth)	0.3	0.275	0.025
BOTTOM OF FOOTING	0.2	0.18	0.02

The analysis showed that the developed 3D model is accurate in most cases where the absolute error is generally low, but the error is found to exceed the industry acceptable limits (1-2 inches) in a few cases, especially when the underlying component is lengthy. This acceptable limit was identified based on our informal discussions with the project manager of this particular construction project. The largest absolute error (0.20 m for component 1) is enough to limit its potential for such construction quality assessment purposes.

ii) Object Completeness Testing and Spatial Deviation Analysis: In order to identify if there are any missing objects or deviations within the captured 3D as-built model, the design BIM model was appended with the as-built model using Navisworks Manage. Spatial deviations were not observed, but some objects were found to be missing from the design model. The missing objects are identified and highlighted in Figure 6.2. It was observed that the as-built model contains additional footing components that were not modeled in the design model. This is due to design changes that occurred in later stages that were missing from the initial design BIM model.

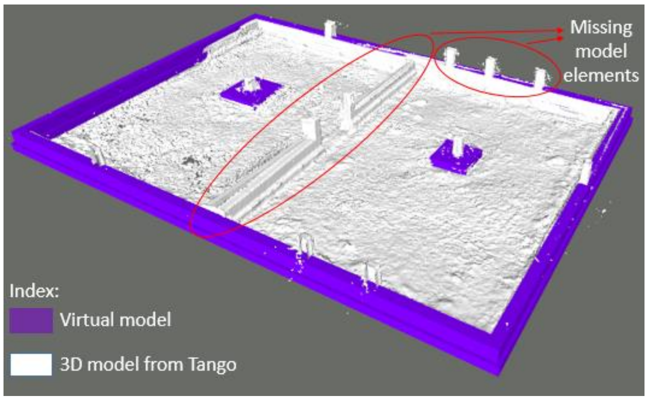
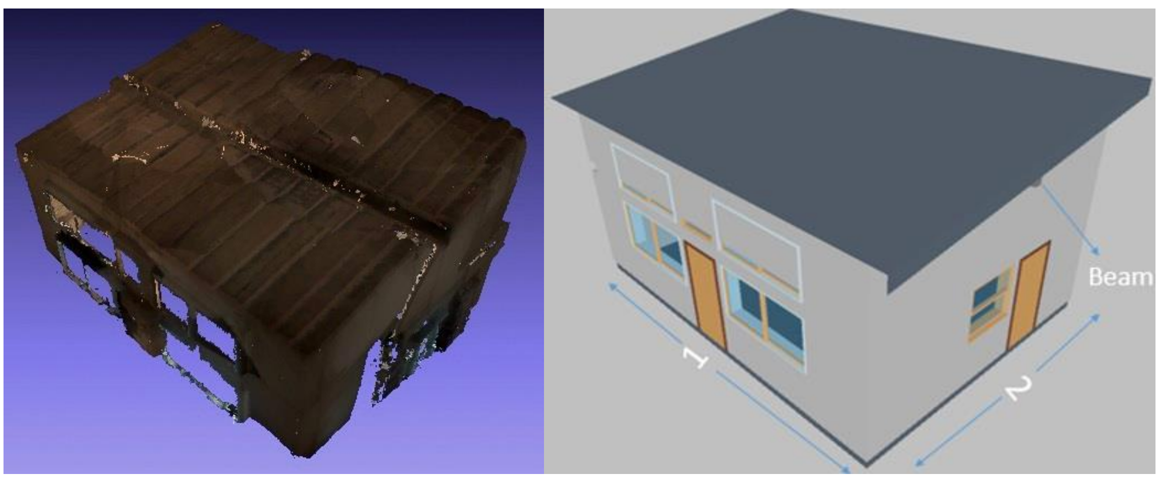


Figure 6.2: Deviations identified between the virtual and as-built 3D models.

Thus, from both these assessment tests it can also be observed how the industry professionals can leverage the initial design BIM model and other BIM tools such as Navisworks to efficiently analyze the accuracy and completeness of the captured as-built data.

- **Interior Hall:**

i) Dimensional Accuracy Analysis: The generated as-built model shown in Figure 6.3(a) was used for conducting the dimensional accuracy analysis. For this, actual dimension values of three different elements highlighted in Figure 6.3(b) were recorded. These values were then compared with those obtained from the captured as-built model. The results were similar to the first case, with some of the component measurements being quite accurate, but the worst cases (e.g., a deviation of 0.35m for an 8m component) is found to be large enough to limit the potential for quality assurance use. These results are also presented in Table 6.4.



(a) (b)

Figure 6.3: (a) As-Built model generated via Tango; (b) 3D BIM Model highlighting the selecting components for accuracy testing.

Table 6.4: Dimensional accuracy analysis of the interior hall 3D as-built model.

Component IDs in Figure 6.3(b)	Measured dimensions from site (m)	Dimension from as-built model (m)	Absolute Diff. (Δ)
1	8	7.65	0.35
2	5.72	5.65	0.07
3 (Beam Depth)	0.25	0.235	0.015

ii) *<u>Object Completeness Testing and Spatial Deviation Analysis:</u>* The object completeness test showed that there are no missing objects in the as-built model, but the deviation analysis showed some discrepancies. One such discrepancy is the mismatch of several window locations. There is a significant offset observed as highlighted in Figure 6.4. This is suspected to arise due to the inability of mobile laser scanners to capture reflective surfaces.

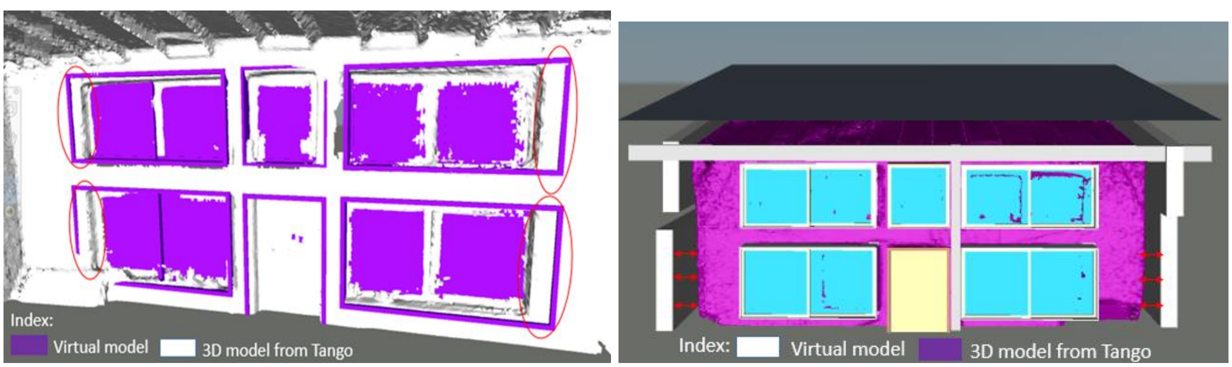


Figure 6.4: Deviations observed in the windows location.

Thus, the accuracy of the captured 3D as-built model is assessed and the various limitations that can affect the use of mobile laser scanning to address this use case scenario were identified.

2. **Data Interoperability and Sharing:**

   During these direct tests on different building components, the data interoperability and sharing requirement were also assessed. It was found that the data format in which the mobile laser scanner generates the final 3D as built model (.obj, .xyz, .pty) is quite standard and the model was easily transferred or shared among different software used by current industry professionals. Thus, no major limitations were observed as per this particular requirement.

3. **Time Required to Capture and Analyze:**

   During the data collection and post-processing steps, the time required to capture and process the generated 3D as-built model is also tracked. It was noted that in both the cases (foundation, interior room) the time required to capture the required data is more than that required by the current traditional practice. This is due to various processing/tracking issues within the technology. Repeated scans had to be taken due to several tracking issues which resulted in increased time for generated the final as-built model. Also, it is observed one of the other major issue which the user can face while using the mobile laser scanners to capture interior environments is the noise from unnecessary objects in the interiors. This sometimes made the post-processing stage quite difficult leading to more time being spent here. Thus, the time requirement can impact the potential of mobile laser scanners to address this particular use case scenario.

4. **Impact of Weather/Surrounding Conditions:**

   Although the mobile laser scanner was conveniently used to scan the interior hall, it was observed that the surrounding weather conditions had an impact while it was used for scanning the foundation. It was observed that surrounding infrared light from the sun impacts the ability to use mobile laser scanners in such environment. In order to avoid this hurdle, the use has to conduct their scans during evening times/before sunset, since that is when the amount of surrounding infrared light is minimum. This particular limitation can also impact the mobile laser scanner's potential.

Thus, the potential of mobile laser scanners to address this particular use case is assessed as per the project team requirements using the developed framework implementation approach.

6.2.1.2 Use Case 2 - Capturing As-Built Conditions of Existing Buildings

For testing the use of mobile laser scanners to address this particular use case, Cadillac Fairview Shopping Mall case study was chosen. First, the existing drawings are validated through traditional methods like a tape measure to set up a benchmark for comparison. Then the store space is captured in the form of the 3D as-built model using a mobile laser scanner. The suitability of mobile laser scanners for addressing this particular use case is then again assessed as per the project team requirements based on the steps laid out in section 5.3.1.2

1. Data Accuracy and Suitability Evaluation:

i) <u>Dimensional Accuracy Analysis</u>: The generated as-built model used for conducting this analysis is represented in Figure 6.5. The dimensions from this as-built model is compared with those provided in the design drawings as part of the dimensional accuracy analysis. The components chosen for this comparison is highlighted in Figure 6.6 The accuracy testing showed similar results to those observed which testing the technology to address the previous use case scenario. A few cases were observed where the deviations were found to be well beyond the industry acceptable limits (1-2 inches) thus severely limiting its potential for use in capturing existing as-built conditions. The project architect who was involved with this study also expressed a similar level of acceptable limit similar to the one mentioned by the project manager during the previous testing. The results are also presented in Table 6.5.

Figure 6.5: 3D as-built model generated via Tango which is then tested for dimensional accuracy.

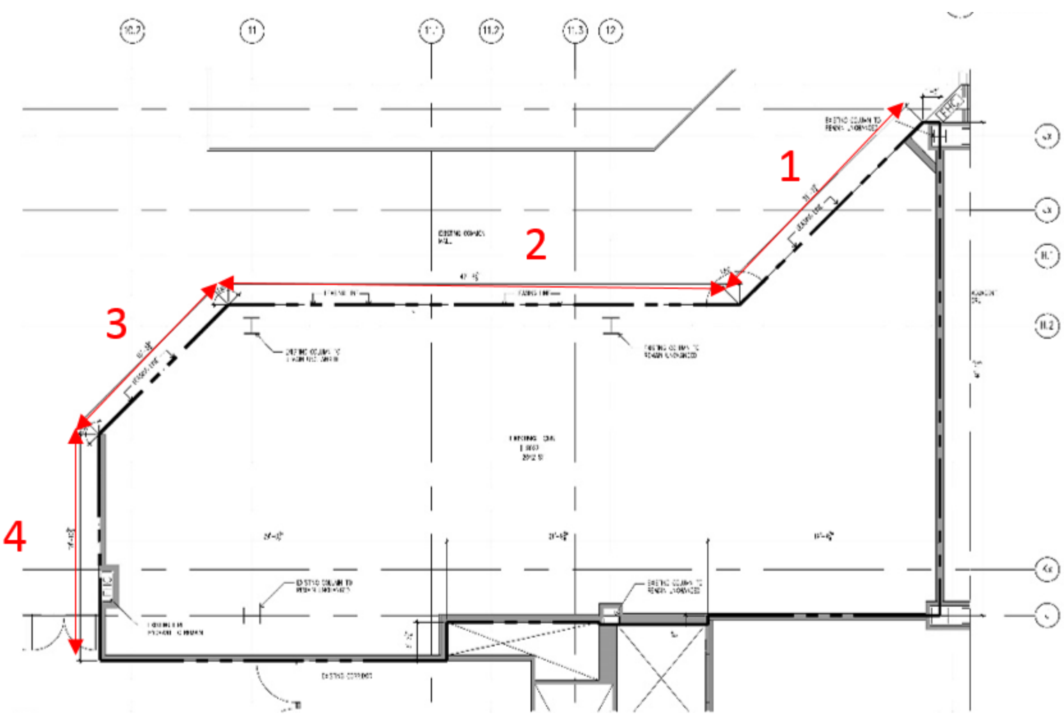


Figure 6.6: 2D design drawing highlighting the selecting components for accuracy testing.

Table 6.5: Dimensional accuracy analysis of the captured 3D as-built model.

Component IDs as shown in Figure 6.6	Measured dimensions from site (m)	Dimension from as-built model (m)	Absolute Diff. (Δ) (m)
1	6.71	6.76	0.05
2	12.80	13.08	0.28
3	5.54	5.77	0.23
4	6.65	6.60	0.05

ii) *<u>Object Completeness Testing and Spatial Deviation Analysis:</u>* The object completeness test showed that the as-built model failed to capture several objects that were present on-site. It is observed that the ducts and pipes layout observed in the store room and the ceiling of the store were not captured in the as-built model. These are highlighted in Figure 6.7 (a), (b). This was possibly due to the inability of mobile laser scanning technology to capture black, reflective, and small surfaces. Spatial deviation analysis also showed that the as-built model recorded the space to be inclined at specific store edges that were not observed nor indicated in the store drawings. These deviations are highlighted in Figure 6.8.

(a) (b)

Figure 6.7: (a) Ducts layout that is not captured in the model; (b) Store ceiling that is not captured.

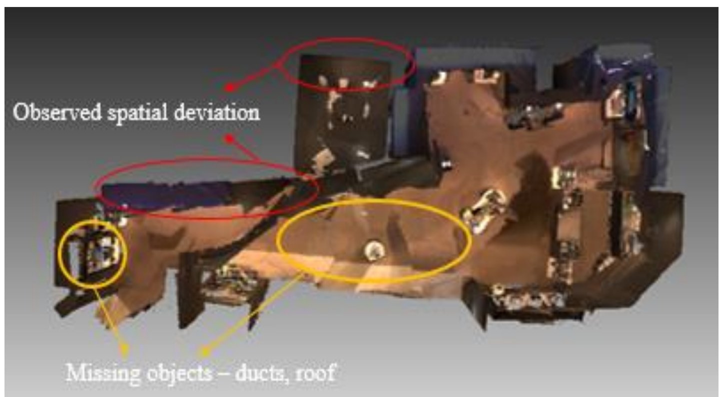


Figure 6.8: Deviations observed in the captured 3D as-built model.

2. **Data Interoperability and Sharing:**

During this direct testing, no significant data interoperability and sharing issues were recorded. It was found that the data format in which the mobile laser scanner generates the 3D as-built model is quite standard (.obj, .xyz, .pty) and the model was easily transferred or shared among different software used by current industry professionals for this particular use case.

3. **Time Required to Capture and Analyze:**

   During these tests, it is again noted that the time required to capture the required data is more than that required by the current traditional practice. Also, it was observed that the noise from decorative/non-structural objects caused severe capturing issues. The noise from such objects also resulted in difficulties during post-processing stage, leading to more time being spent in that stage as well, thus affecting the potential of mobile laser scanners to address this particular use case.

4. **Impact of Weather/Surrounding Conditions:**

   While scanning the required space, no significant impact was observed due to the surrounding conditions since the scanning is conducted in interior conditions where the surrounding infrared light from the sun is minimal.

Thus, the potential of mobile laser scanners to address this particular use case is also assessed as per the project team requirements using the developed framework implementation approach.

6.2.2 Spherical Imaging

After the mobile laser scanning technology is assessed, the spherical imaging technology is then tested to capture the required as-built data in two other major use case scenarios i.e. Design compliance reviews and the capture of exact built conditions during construction. In order to assess it's potential to address these use case scenarios the technology is first assessed as per the user and management requirements. The results of this assessment were already presented in Table 6.2. After this, the technology is assessed as per the four project team requirements by testing it on relevant case study projects. The study also tested how any existing BIM model data can be leveraged or integrated with the spherical imaging technology so as to increase its effectiveness. This section provides the details of the important findings obtained from these tests.

6.2.2.1 Use Case 3 - Remote Design Compliance Reviews

For testing the usability of spherical images to conduct remote design compliance reviews, Brentwood Town Centre case study was chosen. Periodic site visits were conducted to capture the necessary as-built information in the form spherical images which are then tested to perform design compliance checks remotely. The suitability of spherical images to conduct such design compliance reviews is then evaluated from both the project architect's and project engineer's perspective. The usability of spherical imaging technology is also assessed as per the other project team requirements. All these assessments are conducted by following the steps laid out in Section 5.3.2.2. Besides conducting these assessments, the research also focused on identifying major software interface features necessary for effectively using spherical images to address this particular use case scenario. Such an exercise is conducted because currently there isn't any software solution that is readily available which can help the construction industry professionals in analyzing these spherical images effectively as per their needs. Thus, the major interface features identified during this research work is also listed in this section.

1. **Data Accuracy and Suitability Testing:**

   This testing focused on assessing the suitability with respect to the needs of both architects and engineers who are often responsible for conducting such deficiency reviews.

i. *Project Architects:*

The spherical images were taken at different locations on project site with the help of project coordinator located on-site. Then, different possible issues are identified and reviewed directly from these spherical images by using different software tools such as Roundme (a spherical image hosting/viewing site) and MS Paint since there isn't any one software tool that can directly be used for these tests. The effectiveness and suitability of the spherical images to conduct such reviews is assessed based on the direct feedback obtained from the principal project architect, the on-site architect, the regional BIM lead, and the senior project manager for this case study.

One example where the project architects (principal and on-site architect) were able to conduct such design compliance checks is highlighted Figure 6.9. The annotations within those spherical images were done using MS Paint since that feature isn't currently available in Roundme. The project architects were also able to communicate such identified issues to other team members by utilizing the in-built commenting feature within Roundme as shown in Figure 6.10. Also, the image quality of the captured spherical images is found to be good enough by them. However, it is expressed that conducting such deficiency reviews remotely is sometimes not feasible due to various reasons. Both the project architects found the use of such spherical images to be especially troublesome when reviewing large project areas. Review of such large project areas often requires a greater number of spherical images to capture the entire project area. This often made it difficult for them to process and analyze such huge amounts of information in an efficient manner.

However, it is found that this limitation can be addressed up to an extent by linking the spherical images with their corresponding BIM images obtained from existing design BIM model. Since, the current case study was a BIM based project, the project team had a fully developed BIM model readily available. This model was then used to generate a sample spherical BIM image which was then used to compare with the corresponding spherical image obtained from project site by placing them side by side. The usefulness of such an integration between BIM and actual spherical image was evaluated by creating a prototype which then allowed the research team to present this idea before the principal architect, regional BIM lead and the senior project manager. This was again done since there aren't any out of the box software solutions that are readily available which can be used for these tests. Such a side by side comparison of both the BIM and actual spherical images as shown in Figure 6.11 was found to be pretty useful by the lead project architect as well as the senior project manager from the contracting firm handling this project. In situations where even such BIM images cannot be of any use, the principal architect, regional BIM lead and senior project manager felt that sending the project team to visit the site is much more effective rather than just relying on spherical images.

Thus, from this initial evaluation conducted with the help of the principal architect, regional BIM lead and senior project manager it is clearly noted that the spherical images are quite suitable to conduct such remote deficiency reviews only if the underlying area to be reviewed is small and not too complex. If the area to be reviewed is rather large and the project team cannot travel to the project site frequently then integration with respective BIM images can help to an extent.

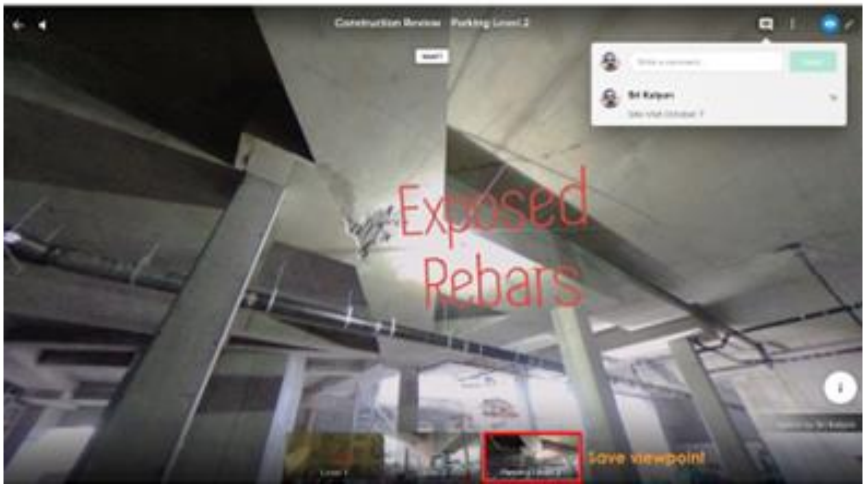


Figure 6.9: Sample issue identified during remote reviews using spherical images.

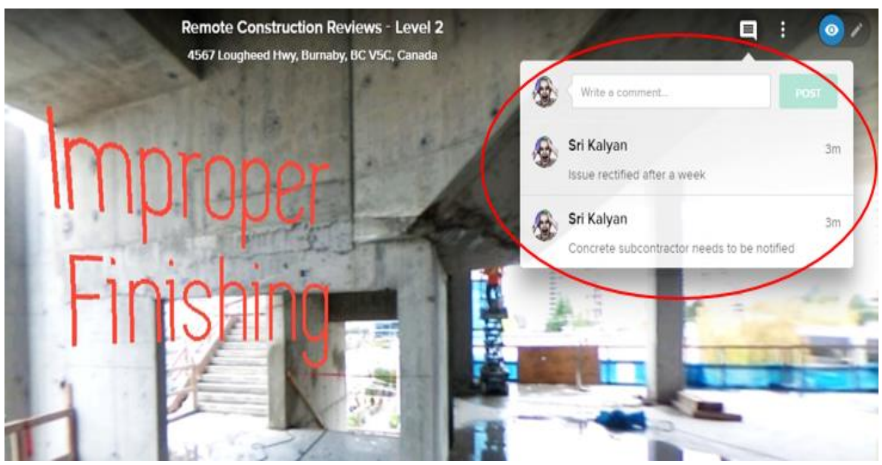


Figure 6.10: Identified issues communicated and tracked using commenting within spherical images.

Figure 6.11: Design compliance review conducted directly by comparison with the spherical image generated from the design BIM.

ii. *Design Engineers:*

The research then focused on testing the use of spherical images to conduct such remote reviews by project engineers. For this, a principal engineer and two other structural design engineers from the design firm (Stantec) were involved in this assessment to gather direct feedback. Spherical images were again taken at different project locations and the information captured in these spherical images was then analyzed by these design engineers to identify various issues. Some of the example issues that the engineers were able to review remotely is highlighted in Figure 6.12. The principal engineer also expressed clearly that these spherical images are indeed much more useful and effective that the current 2D images sent by the contractors on-site. However, both the principal engineer and other structural design engineers expressed difficulties while reviewing areas with significant amounts of rebar laid across the whole site. Since they are required to inspect minute details such as rebar spacing; rebar arrangement; tie hooks etc., the design engineers found it difficult to analyze and inspect such details directly from spherical images, which is highlighted in Figure 6.13. Thus, it is again found that the spherical images cannot replace the whole field review process in its entirety but can act as an assistive technology when reviewing small elements as shown in Figure 6.14.

Figure 6.12: Sample image highlighting how the structural design related issues are reviewed and communicated with team members using only spherical images.

Figure 6.13: Sample images highlighting the significant amounts of rebar in the shear wall foundation that needs to be reviewed occasionally.

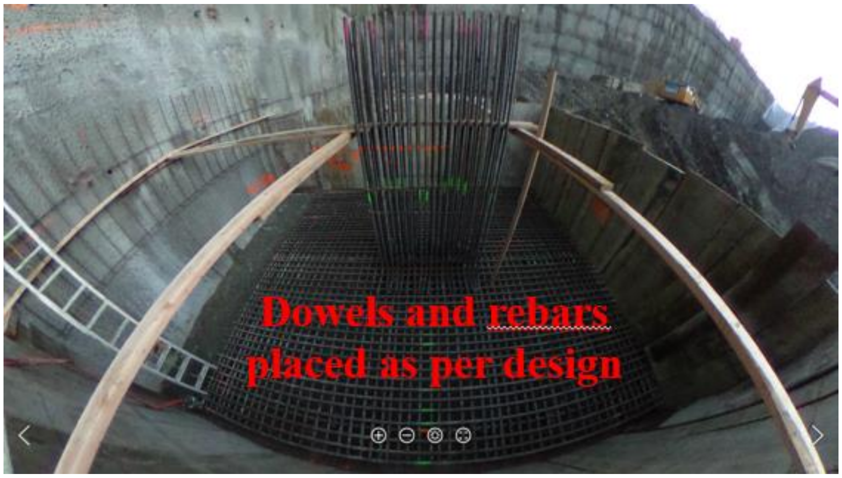


Figure 6.14: Sample image highlighting how small structural elements are reviewed remotely using only spherical images.

2. **Data Interoperability and Sharing:**

   During the testing, no significant data interoperability issues were identified since the spherical images are being captured in a standard data format (.jpeg) which is widely recognized and acceptable among all the different software platforms. Thus, no limitations were observed with respect to this particular requirement.

3. **Time Required to Capture and Analyze:**

   During this direct testing, it was noted that conducting such reviews using the spherical images sent by the person on-site indeed requires much less time when compared to the current traditional practice. This is mainly because of the time saved from avoiding the need to travel to the project site. However, this significant reduction in the time requirement is only observed when the area to be reviewed is rather small and not too complex. In cases where the area to be reviewed is rather large, then the technology is found to be not effective.

4. **Impact of Weather/Surrounding Conditions:**

The quality of the spherical image is impacted by the surrounding conditions such as the light intensity, cloudy conditions etc. up to an extent. But the influence on the final image quality isn't too significant. Also, this potential issue can be addressed by using a much better and more advanced spherical camera acceptable within the project team's budget. Thus, there aren't any limitations with respect to this requirement.

5. **Major Interface Features Necessary to Address This Use Case Using Spherical Images:**

i. *Integration with BIM spherical Images:* This feature is identified to be necessary while reviewing large or complex areas such large architectural design areas; complex mechanical layouts etc as explained earlier. Simultaneous side-by-side comparison of both BIM-based and on-site spherical images as shown in Figure 6.15 can be useful and effective in such cases. Also, through the discussions with the project architects and design engineers during the assessment stage it was expressed that such a feature would also be extremely useful when sharing information with the client/other project personnel who are not comfortable with referring to design drawings to understand any potential issues.

Figure 6.15: Possible integration of BIM based and on-site spherical images for better and easy reviews by comparing and displaying them side-by-side as shown.

ii. *Annotations, Commenting & Sharing:* An ability to add annotations and comments within the spherical images was found to be essential during the initial assessment described earlier. Once the issues are identified from the spherical images they are then required to be shared across all project team members. Thus, the ability to easily add annotations as highlighted in Figure 6.16 plays a crucial role in driving the use of spherical images for conducting field reviews remotely. However, currently this is achieved using other image editing solutions such as MS Paint. Having this feature in-built is very crucial to facilitate the future use of spherical images since the industry professionals aren't comfortable with using too many different software for addressing and analyzing each and every spherical image.

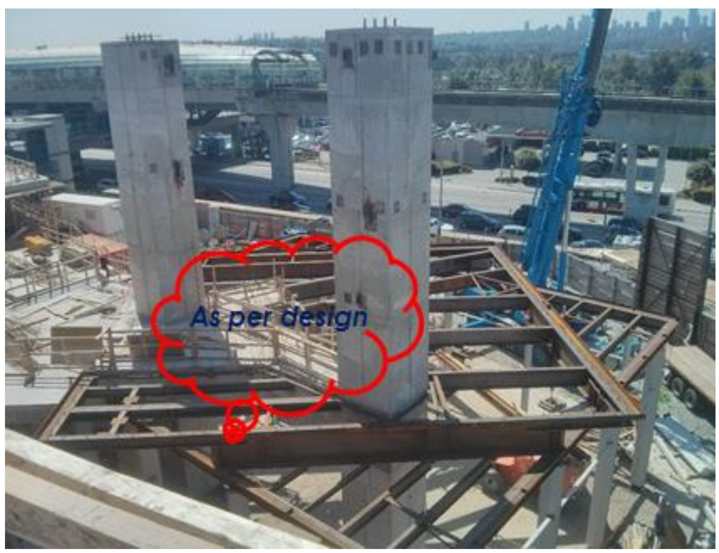


Figure 6.16: Sample image showcasing how the user can annotate directly within spherical images to highlight any observed issues.

iii. *Floor plan integration:* Since the spherical images are required to be taken by a person already present on-site the location of these images have to be identified and tagged so as to better communicate with the reviewers responsible for conducting deficiency reviews. Thus, an ability to tag and integrate the image locations directly within the project floor plans as shown in Figure 6.17 is essential for easy communication. This helps the reviewer in getting a better sense of what is to be reviewed.

Figure 6.17: The spherical images should be tagged onto the floor plans as shown in this figure thus allowing users to quickly identify the location of each image.

Thus, the usability of spherical imaging technology to address this particular use case scenario is assessed as per the different project team requirements. The interface features that are necessary to be included in any software that is going to be developed in the future are also identified.

6.2.2.2 Use Case 4 - Capturing the Exact Built Conditions on Project Site For Owner Use

As-built information capturing the exact/actual built conditions during construction is necessary for project owners to identify the critical building components that are usually embedded within the slabs or enclosed behind the dry walls. This direct testing focuses on evaluating the potential of spherical technology to address this particular use case. For this, the gold house high rise case study was chosen as testing grounds. Periodic site visits were conducted to capture these exact built conditions in the form of spherical images before concrete pouring in slabs happened across multiple levels. The suitability of spherical images to address this use case is then evaluated based on direct feedback from the Site superintendent who is also the owner's representative for this project. His team is responsible for using such information to guide future repair work of this project. The usability of spherical imaging technology is also assessed as per the other project team requirements. All these assessments are conducted by following the steps laid out in Section 5.3.2.2. Besides conducting these assessments, the research also focused on identifying major software interface features necessary for effectively using spherical images to address this particular use case scenario since there is currently no software available targeting the needs of current construction industry.

1. Data Accuracy and Suitability Evaluation:

Once the required images are captured and the information within each image is analyzed their effectiveness is then tested. The critical components such as future power lines, water lines etc. captured within these images are tagged and annotated using MS Paint. The relevant design documents such as the section plans, mechanical equipment specifications are also embedded within the spherical images using Roundme. These are highlighted in Figure 6.18, 31. All of this is done based on the needs that we identified during our informal discussions with the site superintendent. Then the final results are presented to the site superintendent for direct testing and feedback. During these tests, the site superintendent expressed that the spherical images are going to be really effective if such features can be incorporated or recreated with ease by his team members. It was also expressed that these images are much more useful when compared to the current 2D images to conduct any future repairs since the spherical images offers an ability to process and analyze even the surrounding conditions which is not possible with the 2D images. Thus, through these limited tests it is found that the spherical imaging technology indeed has the potential to address such a use case if an easy to use software solution is readily available.

Figure 6.18: Object tagging feature utilized for indicating the approximate location of power lines embedded within the slab.

Figure 6.19: Sample image showcasing how the project team members were able to simultaneously access the relevant section plans at the necessary location.

2. **Data Interoperability and Sharing:**

   During the tests, no significant data interoperability issues were identified since the spherical images are being captured in a standard data format (.jpeg) which is widely recognized and acceptable among all the different software platforms. Thus, no limitations were observed with respect to this particular requirement.

3. **Time Required to Capture and Analyze:**

   The time required to capture and analyze these images is found to be less than that required by the current traditional approach. This is mainly because of the inherent advantage with spherical image since all the surrounding conditions from a given location is captured by a single click whereas in the current approach the user has to take an image from each direction at that location which adds up to the total time if the locations from where such images are to be taken are significantly more.

4. **Impact of Weather/Surrounding Conditions:**

   Through this initial testing, it is observed that the influence of weather conditions on the final image quality isn't too significant. Also, this potential issue can be addressed by using a more advanced spherical camera if necessary. Thus, there aren't any limitations with respect to this requirement.

5. **Major Interface Features Necessary To Address This Use Case Using Spherical Images:**

   These interface features are identified based on observing the needs of potential users while conducting the direct testing described earlier. They are also identified based on the repeated informal discussions with the site superintendent. The major identified features are listed here.

i. *Tagging objects and floor plan integration:* Identifying and tagging critical components like the power lines; water pipelines etc. directly within the spherical images is found to be crucial for effectively using the captured visual information. Also, being able to tag and integrate the image locations with the respective project floor plans on each level is necessary for easy identification of relevant spherical image. These features are expressed to be of significant help to any facilities manager in guiding the future repairs more effectively thus avoiding damage to such critical components.

ii. *Integration with other project documents:* In the current practice the facility manager or contractor refers to various project documents like the design drawings; product specifications etc. so as to identify the relevant properties necessary for effective repair. This is found to be cumbersome since the current visual documentation and the project documents are not linked directly making it inconvenient. Thus, an option to directly integrate the relevant project documents within spherical images at necessary locations is identified to be useful in increasing the overall effectiveness of the proposed system. Such a possible feature is highlighted in Figure 6.20

Figure 6.20: Sample image highlighting how the relevant project documents can be embedded within spherical images which can then be used efficiently during future facilities management.

iii. *Time-scale:* Since the spherical images can be captured at different locations on project site during the entire project duration, the project team members such as the project engineers and the site superintendents expressed a keen interest in being able to link these different images and track the changes that happened over time at each respective location. In the current visual documentation process, the owners have access to only one image at each location taken at some point of time during construction. However, it is found that sometimes the required information is not captured in that single image and the project team members are forced to refer to their own photo repositories in order to find any image that captured the required information. Hence, an ability to link different images that are taken from the same location but during different time instances is essential for addressing this current limitation. Such a possible feature is highlighted in Figure 6.21 which was recreated using certain existing tools.

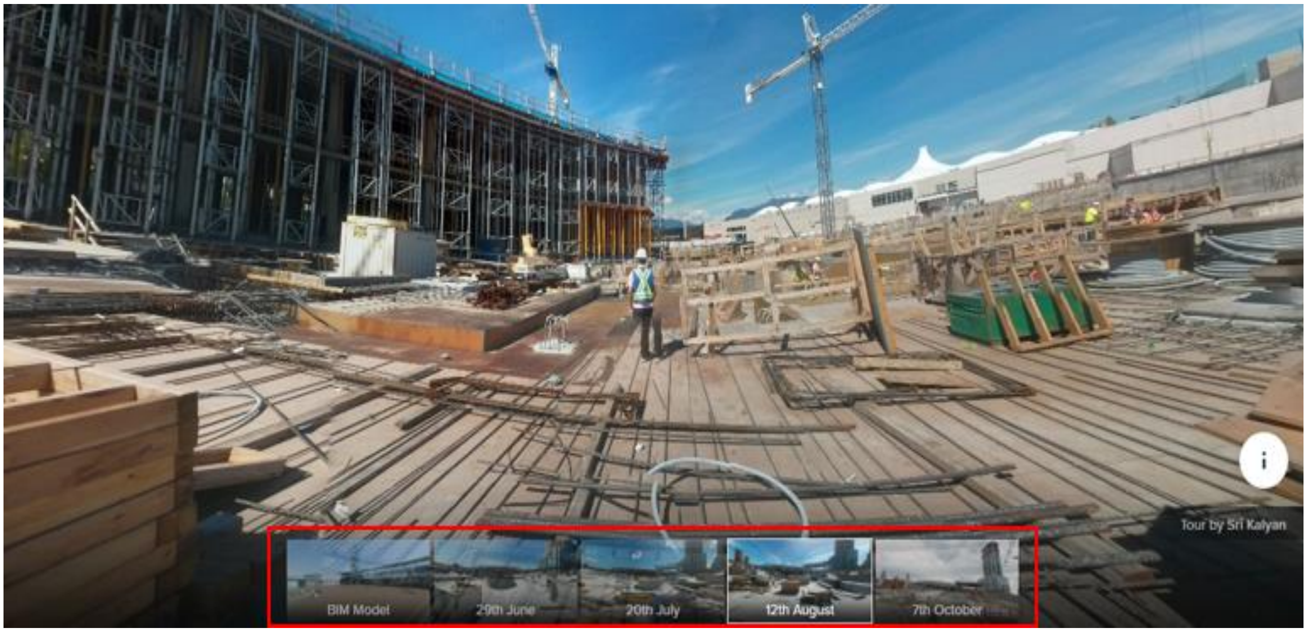


Figure 6.21: Sample image showcasing the possible time scale feature necessary for capturing the evolution of exact built conditions during the entire project duration. The user can quickly transition between these images as highlighted here to track construction progress

Thus, the potential of spherical imaging technology to address this particular use case scenario is assessed as per the different project team requirements. The interface features that are necessary to be included in any software that is going to be developed in the future are also identified as described earlier.

Chapter 7: Discussion

The major benefits and limitations that were observed from testing the two new capture technologies on relevant use case scenarios is discussed in this chapter. The chapter also focuses on discussing the usability of the developed assessment framework and provides some insights into the effectiveness of such an assessment framework. A table comparing the two new capture technologies against the existing capturing techniques is also presented at the end of this chapter. This table was developed based on the assessment framework detailed in this work and also by reviewing some relevant literature works conducted earlier.

7.1 Usability of Mobile Laser Scanning Technology

Through the in-depth assessment, it is found that performing construction quality assessment of critical built components and capturing as-built conditions of existing buildings using mobile laser scanning is not feasible at the current stage due to various limitations highlighted in the findings section. The results showed that the device's use of reflected IR light made depth perception difficult in certain cases, such as modeling black surfaces, duct layouts, and window regions. Furthermore, the results showed that the accuracy of the as-built models created with the mobile laser scanner was generally accurate with few instances of higher deviations. Also, through this study it is found that the time required to capture and analyze the 3D as-built data is relatively high compared to the traditional methods, thus making their application construction industry even more difficult. Although the mobile laser scanners and the required post-processing software are easy to use and costs are not high, other issues such as the lower model accuracy and higher time requirement for capturing and analyzing the data impacts their wide scale usage. Besides that, it is also worth mentioning that the traditional 3D laser scanning and Photogrammetry are well calibrated and established processes which make their usage justifiable in works that require certifications. Hence, it can be concluded that mobile laser scanning is not a working alternative to address these use case scenarios in the current stage. The industry professionals have to rely on using normal 3D laser scanning for capturing as-built conditions in the case of large-scale projects or have to rely on the current traditional methods in case of small scale projects. Further works and improvements are to be done so as to address some of the highlighted limitations before mobile laser scanning can be used as a common technique by working professionals.

7.2 Usability of Spherical Imaging Technology

Also, through the in-depth assessment of spherical imaging technology, it is found that various limitations as highlighted in this study impact its use in conducting remote deficiency reviews. The limitations like its inability to capture key minute details such as the rebar arrangement and other contractual, regulatory requirements restrict the project teams from just relying on spherical images to conduct deficiency reviews. Hence, it can be summarized that on-site inspections cannot be totally replaced with the proposed new capture technology but the project teams can rely on using spherical images for conducting small deficiency reviews remotely. However, it is found that the spherical images are indeed an effective alternative to the current traditional practice for capturing exact built conditions during construction so as to guide future facilities management. The results showed that the project team members found the spherical images to be much more useful compared to other alternatives and no significant limitations have been observed which can limit its usage. Also, it is observed that the time required to capture and analyze data is at par with the traditional practices thus making them the preferred option for visual documentation of exact built conditions.

7.3 Usability of the Developed Framework

Thus, through the implementation of the developed framework different issues with the new capture technologies are identified through a structured assessment process. The framework parameters proved to be quite useful in identifying certain crucial issues that the industry professionals might face when using these new capture technologies. Identification of these crucial issues might not have been possible if the framework didn't provide a structured approach for assessing them. For example, during the initial assessment stage, it is quickly identified that certain contractual and regulatory restrictions might impact the use of spherical images in conducting remote deficiency reviews. Also, the framework helped us in quickly identifying that currently there aren't any out of the box software solutions to help analyze the captured spherical images.

In addition to the above in-depth assessment of each capture technology, an analysis is also conducted to provide a better overview about the advantages and weak points of these new capture technologies in comparison with the other existing techniques. Detailed results of this analysis are summarized in Table 7.1. This analysis is done based on the framework developed in this work and by also studying other related works (Arayici 2008; Bhatla et al. 2012; Klein et al. 2012). Thus, through this research, an assessment framework is first developed to assist in conducting a structured evaluation of any new capture technology suited for addressing different needs of current industry professionals. The framework's usefulness is then demonstrated by implementing it to assess the usability of mobile laser scanning and spherical imaging technologies.

Table 7.1: Comparison of various technologies that can be used for capturing the necessary as-built information.

Category	Assessment Criteria	Model-based capture technologies			Image-based capture technologies	
		Laser Scanning	*Photogrammetry*	*Mobile Laser Scanning*	*Spherical Imaging*	*Traditional Visual Documentation*
User Requirements	*1. Necessary software support*	Often need proprietary software that comes with the device	Need software like Autodesk 123D Catch/Recap for generating 3D as-built point cloud	Need open source software like Meshlab for analyzing the captured 3D as-built point clouds	Need a set of image editing and spherical image viewing software due to the current lack of a single out-of-the-box software that can supports spherical image format for construction industry uses	Do not require any specialized software (image editing and PDF editing software like paint and Adobe are sufficient)
	2. Ease of use	Not easy to use and requires expertise to handle the equipment	Easy to use but requires initial training for efficient data capture	Often easy to use with a minimal learning curve but requires initial training for efficient data capture	Very easy to use with negligible learning curve	Very easy to use
	3. Mobility	Not very mobile.	Highly mobile.	Highly mobile and convenient	Highly mobile and convenient	Highly mobile.
Management Requirements	*1. Device cost*	Highly costly in the range of $50K-$150K.	Affordable in the range of 500-1000$	Affordable with a price tag of around 500-800$	Affordable with a price tag ranging between 500-2000$	Affordable in the range of 500-1000$

Table 7.1: Comparison of various technologies that can be used for capturing the necessary as-built information.

Category	Assessment Criteria	Model-based capture technologies			Image-based capture technologies	
		Laser Scanning	*Photogrammetry*	*Mobile Laser Scanning*	*Spherical Imaging*	*Traditional Visual Documentation*
Management Requirements	*2.Post-processing software cost*	Often need expensive proprietary software	The cost of the required software is less and not that expensive	The required software cost is often minimal/free thus making it quite affordable	The required software cost is very less and is quite affordable	Do not require any specialized software. Most of them are often free
	3.Training time	Involves steep learning curve thus requiring significant training to capture and analyze data	Requires significant training to ensure that the data is captured efficiently	Requires some initial training in order to get the users familiar with the post processing software used for analyzing data	Do not require any additional training. Quick demo of the device and software is enough for getting the users comfortable with its use	Do not require any additional training. Industry professionals are already exposed to the required software
	4. Contractual and Regulatory restrictions	No observed contractual or regulatory requirements that restrict its use	No observed contractual or regulatory requirements that restrict its use	No observed contractual or regulatory requirements that restrict its use	Contractual requirements like compulsory on-site visits can restrict its use for conducting remote deficiency reviews.	No observed contractual or regulatory requirements that restrict its use
Project Team Requirements	*1. Data Accuracy and suitability*	High accuracy and range to the extent of millimeter	High/medium accuracy but loses focus for large distance	Moderate accuracy compared to the other two.	Highly accurate and suitable for visual as-built documentation	Image quality is often high but the still 2D images are not suitable for addressing certain issues

Table 7.1: Comparison of various technologies that can be used for capturing the necessary as-built information.

Category	Assessment Criteria	Model-based capture technologies			Image-based capture technologies	
		Laser Scanning	*Photogrammetry*	*Mobile Laser Scanning*	*Spherical Imaging*	*Traditional Visual Documentation*
Project Team Requirements	*2. Data interoperability and sharing*	Data interoperability is affected by the type of device used for capturing the required data	Data sharing and interoperability among different software and devices is possible due to the existing standards	Data sharing and interoperability among different software and devices is possible due to the existing standards	Easy to share across different software platforms and also among project team members	Easy to share and do not pose any interoperability issues since the data is normal 2D images
	3. Time required to capture and analyze	Huge amounts of time required but the huge amounts of information captured makes it worth. Process easily scalable across projects of different scales.	The time required is often quite more than that of laser scanning/traditional practices. The process is thus not suitable for capturing large-scale projects	The time required to capture and analyze is less compared to the other two but is still more than the traditional practice. The process is also not suitable for capturing large-scale projects.	The time required is very less compared to the traditional practice and the process is easily scalable across projects of different scales.	The time required to capture and generate the final content is relatively high
	4. Weather conditions	Not much affected by weather conditions	Highly affected by weather conditions like cloudy situation	Highly affected by weather conditions like exposure to direct sunlight	A moderate effect on data quality due to weather conditions like dull light etc.	A moderate effect on data quality due to weather conditions like dull light etc.

Chapter 8: Conclusion

In this chapter, the key findings of this research are summarized and some of the major limitations with this research work are highlighted in the two following sections.

8.1 Summary and Lessons Learned

In this study, an assessment framework to evaluate the usability of new as-built capture technologies from the perspective of construction industry is developed. For this, the major industry needs that require as-built information is first identified. The current industry practices followed by the practicing professionals to address these needs are also studied. From this analysis of current industry practices, it is identified that as-built information is required by projects participants including designers, contractors and owners to address four major use case scenarios including assessing the construction quality and compliance to design requirements, capturing existing building conditions for planning upcoming renovations and for guiding future repairs during building operations. From this analysis, it is also identified that the type of as-built data required for addressing these use-case scenarios can be categorized into two types namely: visual and measurement data to capture the visual and spatial information of the project site conditions respectively.

After the analysis of the current industry practices, the framework to assess the usability of new capture technologies was developed by conducting an in-depth industry requirement analysis. This analysis was accomplished through a series of informal discussions with various project team members involved in case study projects chosen for this work. From this analysis, it is identified that the major industry requirements that govern the adoption of any new technology within construction industry can be divided into three set of categories: User, Management, and Project Team Requirements category. Each category focuses on a key set of requirements as felt by various industry professionals depending on their work role. The assessment approach and comparison benchmarks are then setup for each industry requirement as part of the assessment framework. The assessment approach includes qualitative testing techniques such as conducting informal discussions with respective industry professionals or organizing product demos to gather feedback from potential users. The assessment approach also includes direct testing techniques such as trying out the proposed capture technology on different case study projects to evaluate its performance in real world situations. Thus, an assessment framework is developed.

The work then focused on implementing the developed framework to conduct an in-depth assessment of both the mobile laser scanning and spherical imaging technologies. This is done by testing their suitability to address relevant use case scenarios. Through this assessment of mobile laser scanning, it is found that performing construction quality assessment of critical built components and capturing as-built conditions of existing buildings using them is not feasible at the current stage due to various limitations. The results showed that the accuracy of the as-built models is not meeting the required industry acceptable limits. Also, it is found that the time required to capture and analyze the 3D as-built data is relatively high compared to the traditional methods, thus making their application even more difficult.

Also, through the in-depth assessment of spherical imaging technology, it is found that various limitations such as its inability to capture key minute details and other regulatory requirements restrict the project teams from just relying on spherical images to conduct deficiency reviews. However, the analysis showed that the spherical images are indeed an effective alternative to the current traditional practice followed for capturing the exact built conditions during construction. The results showed that the project team members found the spherical images to be much more useful compared to other alternatives since no significant limitations have been observed which can limit its usage. Thus, the developed assessment framework is utilized in evaluating the potential of two new capture technologies to address various use-case scenarios.

8.2 Limitations and Future Work

The assessment framework developed in this work is based on the insights and feedback from the industry professionals working around Vancouver region. So, the results and requirements identified from these discussions can be biased based on local experience and local requirements which might not be the case in other regions. Thus, the ability to generalize the findings of this study across a wider spectrum is affected. Further work should focus on assessing the generalizability of the developed framework by gaining feedback and comments from industry professionals working in other regions. Also, both the technologies that were tested are evaluated on an as-is basis where only currently available software and technology support is used for conducting this assessment. If sufficient collaboration with software vendors was also established, then it would have let to a better assessment since the research team currently couldn't gain any insights into what the software and technology vendors are currently developing to address some of the identified issues with these technologies. Thus, future work can also consider such collaboration to conduct a more accurate assessment of the potential of such technologies.

Also, the work focused on developing the framework and assessing the two new technologies by studying four major use-case scenarios. There might be other major applications for as-built information which the research team failed to catch or observe during their initial study of current industry requirements and practices.

The spherical imaging technology is found to have the potential to replace the current traditional practice for capturing the exact built conditions during construction. However, this was deduced based on some initial testing conducted during this study. The technology was not used by the project team on a real-life project in a full extent. Using the technology on one such project for the entire project duration will provide some key insights into the actual effectiveness and usability of such technology. Such an exercise can also expose some of the limitations that the study failed to capture currently. Thus, in the future, researchers should focus on conducting more in-depth testing of the spherical imaging technology for this use-case.

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